UNIVERSITY OF THE PACIFIC ECOLOGICAL ENGINEERING RESEARCH PROGRAM

Synthesis of Results from Investigations of the Causes of Low Dissolved Oxygen in the San Joaquin River & Estuary in the Context of the Dissolved Oxygen Total Maximum Daily Load

Report 7.1

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Table of Contents

List of Acronyms & Abbreviations

1-D	One dimensional (model)
3-D	Three dimensional (model)
BOD	Biochemical oxygen demand
CBOD	Carbonaceous biochemical oxygen demand
NBOD	Nitrogenous biochemical oxygen demand
Control Plan	State Water Resources Control Board ruling, section 3949.2 of Title 23 of the California Code of Regulations: *The Control Program for Factors Contributing to the Dissolved Oxygen Impairment in the Stockton Deep Water Ship Channel* (California Regional Water Quality Control Board Central Valley Region, 2005)
cfs	Cubic feet per second
Delta	Sacramento-San Joaquin River Delta
DO	Dissolved oxygen
DOC	Dissolved organic carbon
DO TMDL	Dissolved oxygen total maximum daily load
DSM2-QUAL	Delta Simulation Model II with a water quality module
DWR	Department of Water Resources
DWSC	Deep Water Ship Channel
ENOD	Excess net oxygen demand
Flow+500	Link-Node model scenario simulating the effect of increasing flow from the SJR to the Stockton DWSC by 500 cfs.
Link-Node	A 1-D Link-Node model for the SJR estuary between Old River and Disappointment Slough
May_2013 model	Calibration of the Link-Node model completed May 2013
MOS	Margin of safety
No DWSC	Link-Node model scenario simulating the elimination of the river deepening for the Stockton Deep Water Ship Channel.

No RWCF	Link-Node model scenario simulating the elimination of oxygen-demanding substances flowing into the Link-Node domain from the City of Stockton RWCF.
No SJR	Link-Node model scenario simulating the elimination of oxygen-demanding substances flowing into the Link-Node domain from the SJR.
No Tribs	Link-Node model scenario simulating the elimination of oxygen-demanding substances flowing into the Link-Node domain from tributaries other than the SJR.
ODS	Oxygen-demanding substances
QA	Quality assurance
QC	Quality control
Regional Board	California Regional Water Quality Control Board, Central Valley Region
RMA	Resource Management Associates (model)
RRI	Rough & Ready Island (monitoring station)
RWCF	Stockton Regional Wastewater Control Facility
SJR	San Joaquin River
SJR-WARMF	The San Joaquin River version of the Watershed Analysis Risk Management Framework (Model) specifically for use in the San Joaquin River Dissolved Oxygen Total Maximum Daily Load
TDS	Total dissolved solids
TMDL	Total maximum daily load
TMDL-need-A	Studies required as part of the DO TMDL plan for the San Joaquin River to identify and quantify sources of oxygen-demanding substances and their precursors in the DO TMDL source area
TMDL-need-B	Studies required as part of the DO TMDL plan for the San Joaquin River to identify and quantify growth or degradation mechanisms of oxygen demanding substances in transit through the DO TMDL source area to the DWSC

TMDL-need-C	Studies required as part of the DO TMDL plan for the San Joaquin River to identify and quantify the impact of oxygen-demanding substances on dissolved oxygen concentrations in the DWSC under a range of environmental conditions and considering the effects of chemical, biological, and physical mechanisms that add or remove dissolved oxygen from the water column in the DWSC
TWG	Technical working group
Upstream Project	Studies conducted predominately in the riverine San Joaquin River (between Vernalis and Lander Ave.) which include data collection from 2005 and 2007, conducted under the Ecosystem Restoration Program grant ERP - 02D - P63
USEPA	United States Environmental Protection Agency
USGS	United States Geological Survey
WARMF	Watershed Analysis Risk Management Framework (Model)
WARMF-2008	Watershed Analysis Risk Management Framework model version published in 2008
WARMF-2012	Watershed Analysis Risk Management Framework model version published in 2012

Introduction

San Joaquin River & Deep Water Ship Channel

Following its natural course, the San Joaquin River (SJR) originates in the Sierra Nevada Mountains, descends west to the San Joaquin Valley floor, and drains north to the Sacramento-San Joaquin Delta (Figure 1). However, the San Joaquin Valley of California is an example of a highly engineered landscape where the natural ecosystem has been entirely transformed. The hydrologic cycle of the valley is now predominately artificial (Figure 2) and the region's wetlands have been converted almost entirely to irrigated agricultural land (Stringfellow and Jain, 2010). The San Joaquin Valley is engineered to be the most productive agricultural region in the world, despite an average total rainfall of less than 1.3 cm during the major growing season (June to September). The transformation of the San Joaquin Valley has resulted in numerous environmental problems related to the loss of wetland-provided ecosystem services, including excess nutrient exports to surface waters, eutrophication, and low dissolved oxygen (DO) areas in the SJR estuary, as well as numerous other surface water, ground water, and air pollution problems (e.g. Lin *et al.*, 2002; Hall and Anderson, 2003; Jassby and Nieuwenhuyse, 2005; Stringfellow, 2008c; Stringfellow *et al.*, 2008c, Stringfellow *et al.*, 2009, Stringfellow and Jain, 2010).

Although water quality problems persist throughout the SJR system, low DO conditions are largely restricted to the SJR estuary (Figure 3) including the Stockton Deep Water Ship Channel (DWSC). The DWSC has been deepened for navigation and has had a long-term problem with low DO conditions (McCarty, 1969; Bain et al., 1970; Gowdy and Grober, 2003). The DWSC is also part of a salmon migration route and resolution of the low DO conditions is a major focus of ecosystem restoration efforts and TMDL implementation in California (Lehman, 2001; Foe et al., 2002; Gowdy and Grober, 2003; Stringfellow *et al.*, 2003; Jassby, 2005; Herr and Chen, 2007; Litton et al., 2007; Stringfellow et al., 2007b; Young and Kendall, 2007; Stringfellow et al., 2008b).

Low Dissolved Oxygen Total Maximum Daily Load (DO TMDL) & Water Quality Objectives

Water quality objectives for minimum DO concentrations in Delta waters were established in the *Water Quality Control Plan (Basin Plan) for the Sacramento River and San Joaquin River Basins* (California Regional Water Quality Control Board Central Valley Region, 1998, 2009). The Basin Plan defines DO impairment as any time the DO concentration falls below the water quality objectives, established in the Basin Plan, of 6 mg/L from September 1 to November 30 and 5 mg/L during all other times of the year (California Regional Water Quality Control Board Central Valley Region, 1998; 2009). When dissolved oxygen concentrations in the DWSC are below Basin Plan objectives, the assimilative capacity of the water column for oxygen demand has been exceeded. In 2005, the Central Valley Water Board adopted Resolution No. R5-2005-0005 establishing a Control Plan for factors contributing to the dissolved oxygen impairment in the Stockton Deep Water Ship Channel (California Regional Water Quality Control Board Central Valley Region, 2005). The Control Plan includes, as part of its implementation requirements, a Total Maximum Daily Load (TMDL) directed to the point and nonpoint source discharge of pollutants that contribute to the DO impairment (California Regional Water Quality Control Board Central Valley Region, 2005).

DO TMDL & Excess Net Oxygen Demand (ENOD)

The TMDL program is intended to control factors contributing to the DO impairment in the DWSC, not just establish water quality objectives. The Control Plan establishes a control program for factors contributing to the net oxygen demand over and above the assimilative capacity of the river at the DWSC. The Control Plan defines a quantitative measure of assimilative capacity: excess net oxygen demand (ENOD). When the assimilative capacity of the river is exceeded and the DO concentration falls below the regulatory objective, the ENOD is calculated as the difference between the actual DO concentration and the DO objective times the flow to yield a quantitative measure of how much the assimilative capacity of the river has been exceeded, in mass of ENOD (California Regional Water Quality Control Board Central Valley Region, 2005). The details of the ENOD calculation are further described in the Methods section.

Causes of Dissolved Oxygen Impairment

Low DO conditions in any body of water are the result of the balance that occurs between physical, chemical, and biological processes that serve to add or subtract soluble oxygen to the water column (e.g. Balls *et al.*, 1996; Rabalais *et al.*, 2002; Breitburg *et al.*, 2003; Jassby and Nieuwenhuyse, 2005; Stringfellow *et al.*, 2007a; Bricker *et al.*, 2008; Shields and Weidman, 2008; Sullivan *et al.*, 2010). Briefly, oxygen is added to the water column by photosynthesis, import from adjacent waters, and reaeration. Oxygen is removed from the water column by degassing and reactions with reduced organic or inorganic compounds, collectively referred to as oxygen demanding substances (ODS). Reactions between oxygen and reduced organic and inorganic compounds are typically mediated by microorganisms that use the reduced compounds for growth. The balance that occurs between processes adding oxygen and processes removing oxygen is in part dependent on channel geometry and hydraulics. Channel geometry influences oxygen balance through its effect on factors such as surface to volume ratio and the depth to which light penetrates (photic zone) in the water column, which is important to reaeration and degassing processes. Hydraulics influence processes such as mixing and residence time, which effect biological processes and the balance between the rate of oxygen depletion, importation, and reaeration (Stringfellow *et al*., 2007a).

Types of ODS found in the SJR system include carbon associated with phytoplankton and inorganic ammonia-nitrogen associated with wastewater discharge. Phytoplankton grow abundantly in the SJR, because it is a eutrophic river, rich in nutrients, and it is warm, shallow, and exposed to abundant sunlight (Lehman, 1992; Leland *et al.*, 2001; Kratzer *et al.*, 2004; Lehman *et al.*, 2004; Jassby and Nieuwenhuyse 2005; Volkmar and Dahlgren, 2006; Ohte *et al.*, 2007; Stringfellow *et al.*, 2008a; Stringfellow *et al.*, 2009; Volkmar *et al.*, 2011). There is a correlation between the concentration of phytoplankton (as measured by chlorophyll-a photosynthetic pigments) and biochemical oxygen demand (BOD) in the SJR (Volkmar and Dahlgren, 2006; Ohte *et al.*, 2007; Stringfellow *et al.*, 2009). Since phytoplankton are a contributing factor to ODS and phytoplankton grow in the SJR due to eutrophication from input of nutrients, the sources of the nutrients nitrogen and phosphorous need to be understood when quantifying the sources of ODS and their precursors in the SJR.

Joint Responsibility for ENOD

Based on a review of numerous studies, the California Regional Water Quality Control Board Central Valley Region (Regional Board) established that the DO impairment of the DWSC is caused by three factors: low flow, channel geometry, and the level or amount of ODS in the DWSC (California Regional Water Quality Control Board Central Valley Region, 2005). To our knowledge, the TMDL is unique in the nation in that it assigns responsibility for control of ENOD in the river jointly between those parties collectively responsible for the DWSC geometry and those parties collectively responsible for reduced DWSC flow, and those parties collectively responsible for discharging ODS to the DWSC.

In the Control Plan, the responsibility for ENOD was apportioned among the contributing factors according to an initial assessment, where 30 percent was apportioned to discharge, or effluent, from the City of Stockton Regional Wastewater Control Facility (RWCF); 60 percent to nonpoint sources, which include discharges from irrigated land and those responsible for the maintenance of the DWSC; and 10 percent from unknown or minor sources (California Regional Water Quality Control Board Central Valley Region, 2005). The Control Plan includes a margin of safety (MOS) equal to 20% of ENOD to account for technical uncertainty and an adjustment factor was included to account for flow measurement error (California Regional Water Quality Control Board Central Valley Region, 2005).

Studies Required for the DO TMDL

The DO TMDL for the SJR estuary requires responsible entities to engage in studies of the causes of ENOD (California Regional Water Quality Control Board Central Valley Region, 1998, 2005, 2009). The DO TMDL identifies a "source area" subject to investigation of factors contributing to or causing low DO conditions in the SJR (Figure 4). The causes of ENOD are complex and the TMDL identified studies needed to answer fundamental questions concerning root causes of ENOD in the San Joaquin River and Estuary.

The TMDL required that studies must be conducted to identify and quantify:

(a) Sources of oxygen demanding substances and their precursors in the dissolved oxygen TMDL source area (TMDL-need-A)

(b) Growth or degradation mechanisms of these oxygen demanding substances in transit through the source area to the DWSC (TMDL-need-B)

(c) The impact of these oxygen demanding substances on dissolved oxygen concentrations in the DWSC under a range of environmental conditions and considering the effects of chemical, biological, and physical mechanisms that add or remove dissolved oxygen from the water column in the DWSC (TMDL-need-C)

These studies were required in both the TMDL Control Plan and the amended Basin Plan (California Regional Water Quality Control Board Central Valley Region, 2005, 2009). In this report we summarize studies conducted to meet these requirements of the DO TMDL and discuss the results of the most recent study in the context of the DO TMDL study objectives.

Upstream SJR Project (2005 – 2007)

Studies were conducted in 2005 through 2007 that investigated sources of ODS and ODS precursors in the DO TMDL source area (TMDL-need-A) and transformation mechanisms for ODS and ODS precursors (TMDL-need-B). Collectively, these studies were designated the "Upstream San Joaquin River DO TMDL Project" (Upstream Project). This project was geographically limited to the riverine portion of the SJR, approximately between Vernalis, the legal limit of the Sacramento-San Joaquin River Delta (Delta), and Lander Avenue (Figure 5, locations 5 and 10 respectively), with the exception of a study examining mass transport of phytoplankton between Mossdale (site 4 in Figure 5) and the DWSC (site 427 in Figure 5) (Litton *et al.*, 2008).

In the Upstream Project, field work and sample collection was originally only planned for 2005 and 2006; however, 2005 and 2006 were wet years and SJR flows were very high, so as part of the adaptive management strategy for the Upstream Project, field work was continued in 2007, which was a very low flow year. The Upstream Project was completed in June 2008 (Stringfellow, 2008a; Stringfellow *et al.*, 2008a) and a complete version of the final report is available for download at *http://eerp.org/*.

The results of the Upstream Project included a wealth of monitoring data and other information useful for determining the sources of ODS in the SJR (TMDL-need-A) (Stringfellow *et al.*, 2008b; Stringfellow, 2008b, 2008c). This data was subject to an initial analysis that identified sources and quantified loads of ODS and precursors entering the SJR (TMDL-need-A) using an averaging method (Stringfellow, 2008a). In the current study (Estuary Study, described below), the use of averaging methods for identifying source loads was validated (Gulati *et al.*, 2013) and a mass balance on the SJR between Lander Avenue and Vernalis, the legal limit of the Delta, was calculated (see below).

As part of the Upstream Project, a model was developed to address TMDL-need-B and examine the transformation of ODS in the riverine (non-tidal) portion of the SJR (Systech Water Resources Inc., 2008; Stringfellow *et al.*, 2009). The model used in the Upstream Study was based on the Watershed Area Risk Management Framework (WARMF) model, an open source USEPA TMDL model (Keller, 2000; Herr and Chen, 2012). The WARMF model was adapted specifically to the SJR as part of the Upstream Project. The SJR-Version of WARMF (SJR-WARMF), specifically developed for use in the DO TMDL, was published in 2008 (WARMF-2008) as part of the Upstream Project deliverables (Herr *et al.*, 2008a).

The WARMF-2008 model is a one-dimensional (1-D) model that largely uses records of observed data as inputs for most subwatersheds to the SJR and then simulates river processes to generate output as a function of distance downstream. The WARMF-2008 model has the functionality to model landuse and associated subwatershed processes, but this functionality was not used to model most subwatershed inputs in SJR-WARMF since observational data was available. The WARMF-2008 model was calibrated for simulation of hydrology, total dissolved solids (TDS), phytoplankton, and other water quality parameters (Herr and Chen, 2006a). The WARMF-2008 model was calibrated specifically to be used by the Regional Board and other stakeholders as a tool to support implementation of the TMDL in the riverine portion of the SJR (Herr and Chen, 2006a; Herr and Chen, 2006b; Herr and Chen, 2007; Herr *et al.*, 2008b; Herr and Chen, 2012). The WARMF-2008 model was used for determining the growth and degradation of phytoplankton in the SJR upstream of the estuary (TMDL-need-B) (Herr *et al.*, 2008b; Stringfellow, 2008a; Stringfellow *et al.*, 2008a).

From 2005 to 2008, regular meetings of the DO TMDL Technical Working Group (TWG) were held and projects related to the low DO condition in the DWSC were reviewed and discussed (http://www.sjrdotmdl.org/). Although the Upstream Project was limited to a study of the non-tidal portion of the SJR, as part of the adaptive management process, as directed by the TWG, the WARMF-2008 model for the riverine SJR was integrated with the Systech Link-Node model using a graphical user interface (Herr and Chen, 2006a; Jones and Stokes, 2006). The Link-Node model is a 1-D model for the SJR estuary between Old River and Disappointment Slough (Figure 6).

DWSC Projects (2005 – 2007)

Although the Upstream Project did not include an investigation of the tidal estuary and the DWSC (Figure 5), other studies were conducted in the estuary by researchers at UC Davis, Stanford, and United States Geological Survey (USGS), who investigated the use of three dimensional (3-D) models for describing the impact of ODS in the DWSC under a range of environmental conditions (Doyle *et al.*, 2008; Monismith *et al.*, 2008). The UC Davis/Stanford/USGS model considered the effects of chemical, biological, and physical mechanisms that add or remove dissolved oxygen from the water column in the DWSC, and was therefore in alignment with TMDL-need-C. Modeling studies were also conducted by HydroQual, a consulting firm, to investigate the use of their 3-D model, ECOMSED/RCA for application to the DO TMDL (HydroQual, 2006).

Results from these modeling studies were presented to the DO TMDL TWG in a public forum during a series of meeting in 2005 and 2007 that are documented on the TWG website (http://www.sjrdotmdl.org/). The use of 3-D models for TMDL management was evaluated and compared to 1-D models that had been used previously for modeling water quality in the DWSC. The 1-D models that had been used previously include the Resource Management Associates (RMA) model, the Systech Link-Node Model, and the Department of Water Resources (DWR) Delta Simulation Model II with a water quality module (DSM2-QUAL) (Jones and Stokes, 2006).

A technical summary of the conclusions of those discussions was written and published by Jones & Stokes at the behest of the California Bay-Delta Authority and the TWG (Jones and Stokes, 2006). In brief, it was concluded that 3-D models had research value, but were not inherently more accurate or useful for predicting low DO conditions in the DWSC than 1-D models (Jones and Stokes, 2006). Further studies found that although the DWSC may stratify, the stratification is not stable and the DWSC turns over or mixes on a daily basis, even in summer (Lehman et al., 2004; Monismith et al., 2008). The lack of stable stratification may explain why 1-D models appear adequate for modeling the DWSC and the Delta.

The DO TMDL TWG selected to go forward with a 1-D model for use with the DO TMDL process. The RMA model, the Link-Node model, and the DSM2-QUAL model were considered for use in the DO TMDL (Jones and Stokes, 2006). The RMA model was not in current use to the knowledge of the TWG and was similar in many respects to the Systech Link-Node model, so the RMA model was eliminated from consideration for use in the DO TMDL by members of the TWG. The DSM2-QUAL is used by DWR for the dynamic simulation of one-dimensional hydrodynamics, water quality, and particle tracking in the Delta (California Department of Water Resources, 2001, 2013). The DSM2-QUAL model did not have a graphical user interface that would allow "non-experts" to use the model and there was concern from stakeholders that the use of DSM2-QUAL would not support stakeholders need to develop a management plan in response to anticipated DO TMDL allocations. The Systech Link-Node model had a graphical user interface and had been used previously in a regulatory context, as part of the DO TMDL development, for examining low DO conditions in the DWSC (Chen and Tsai, 2000; Chen and Tsai, 2002; Lee and Jones-Lee, 2003). Furthermore, the Link-Node model was integrated with the SJR WARMF model by the graphical user interface, allowing the modeling of riverine and estuarine processes together. Based on the evaluation by the TWG, the Systech Link-Node model was selected for development and improvement. Improvement and calibration of the Link-Node model was eventually included as part of the Upstream Study, as part of Task 6, under the adaptive management plan (Herr and Chen, 2006a).

SJR Estuary Project (2011 – 2013)

In order to complete the studies specified in the DO TMDL (TMDL-needs-A, -B, and -C), a project was planned and approved for initiation in 2008. The objectives of the "Estuary Project" were to complete the necessary measurements, modeling, and other scientific investigations needed to support DO TMDL implementation. This report summarizes and synthesizes the results of the Estuary Project. A complete description of scientific and engineering activities conducted as part of the Estuary Project can be found in technical reports provided as a supplement to this report. Table 1 has a list of the technical reports and titles. The reports can be downloaded from the EERP website (http://www1.pacific.edu/eng/EERP2/).

The objectives of the project included continued sampling in the Upstream study region (see Report 4.1.1, 4.1.2, 4.2.1, and 4.2.2) and improved development of land-use aspects of the WARMF-2008 model (Report 5.2.1, 5.2.2, and 5.2.3), but the focus of the Estuary Project was on the DWSC and surrounding SJR estuary region, which had not been fully investigated as part of prior studies. A major goal of the project was to further develop the Link-Node model as a water quality model for the DWSC that could be used in the context of the DO TMDL. Other goals of the Estuary Project addressed outstanding issues related to understanding the impact of all of the identified contributing factors on DO concentrations in the DWSC (TMDL-need-C), including investigation of zooplankton and cyanobacteria blooms in the project study region (Report 4.4.1, 4.4.2, 4.5.1, and 5.6.1), high resolution spatial measurements in the DWSC (Report 4.8.6 and 4.8.7), and an analysis of low DO condition in the region of the Old and Middle Rivers (Figure 3, Report 4.3.1). Complete documentation of the DO Estuary Project can be found in the attached appendices.

Due to economic factors, the project start was delayed from 2008 until 2011. This delay added complications to the project, since the SJR-WARMF model had been extensively modified since the WARMF-2008 version was published at the completion of the Upstream Project (Larry Walker & Associates *et al.*, 2010; Systech Engineering Inc., 2012; U.S. Bureau of Reclamation, 2012a, b). As part of the adaptive management process for the Estuary Project, the utility of the modified SJR-WARMF model published in April 2012 (WARMF-2012) was tested for use in SJR DO TMDL management. In the more recent versions, WARMF was changed for purposes unrelated to the management of the DO TMDL (Larry Walker & Associates et al., 2010; Systech Engineering Inc., 2012; U.S. Bureau of Reclamation, 2012a,b). One major change was that the newer WARMF model versions incorporated extensive land-use functionality that was not included in the WARMF-2008 model. Although examining landuse functionality in the context of DO TMDL management was an objective of the Estuary Project, the reliance of landuse functionality in the WARMF-2012 model limited its use in addressing TMDL-need-A and –B without extensive validation. Under the adaptive management strategy, both the WARMF-2008 model, specifically developed for the DO TMDL, and a newer version of the SJR-WARMF model published in 2012 (WARMF-2012) were evaluated in this study.

As stated above, a major objective of the Estuary Project was to improve and calibrate the Link-Node Model for use in understanding the effects of chemical, biological, and physical mechanisms on DO and ENOD in the DWSC (TMDL-need-C). The modifications introduced by the WARMF-2012 model also complicated objectives related to evaluating the Link-Node model for DO TMDL management in the estuary. The Link-Node model was integrated with the WARMF model via a graphical user interface, although the Link-Node model had not been significantly changed when landuse functionality was added to WARMF after 2008. As part of the Estuary Project, the Link-Node model was improved and recalibrated (Report 5.1.1), however the improved Link-Node model was integrated with the more current SJR-WARMF model, not the version specifically developed for the DO TMDL management. Under the adaptive management strategy, the Link-Node model was evaluated independently of all versions of the SJR-WARMF model. For independent evaluation, measured flow and water quality data was used as input to the Link-Node model, rather than output from any version of the SJR-WARMF model (see Report 4.8.5 for details).

Synthesis Report Objective

In this report we present and discuss results of the Estuary Project (E0883006, ERP-08D-SO3) that specifically relate to the studies mandated in the DO TMDL (California Regional Water Quality Control Board Central Valley Region, 2005). This report synthesizes results from studies examining direct measurements of diffuse discharges in the upstream region of the SJR with results of modeling studies conducted using the WARMF-2008 and WARMF-2012 models (Report 4.8.1, 4.8.2, 4.8.3, and 4.8.8). The results of these studies are used to identify sources of oxygen demanding substances and their precursors and define the growth and degradation mechanisms of oxygen demanding substances in transit through the source area to the DWSC (TMDL-needs-A and -B). Studies were conducted examining the accuracy and precision of the current calibration of the Link-Node model and use of the Link-Node model to identify and quantify causes of ENOD. These results are discussed in the context of using the Link-Node model to address outstanding issues related to understanding the impact of all of the identified contributing factors on DO concentrations in the DWSC (TMDL-need-C). Studies and monitoring activities conducted as part of the Estuary Project are documented in detail in the scientific reports attached as appendices. A list of reports is provided in Table 1.

Methods

Study Area

The San Joaquin Basin drains approximately 11,400 mi^2 in central California. In this study, the focus is on the 7,395 mi^2 basin of the perennial San Joaquin River, which includes the

SJR and estuary between Lander Ave. and Disappointment Slough (Figure 7). The study area is described in detail in USGS reports and other publications (Kratzer et al., 2004; Quinn et al., 2005; Volkmar and Dahlgren, 2006; Ohte et al., 2007; Saleh et al., 2007; Stringfellow, 2008b; Stringfellow, 2008c; Stringfellow et al., 2009; Kratzer et al., 2011). Land use in the San Joaquin Valley is dominated by agriculture (Figure 7), which has greatly altered the land surface, including the flow path of the SJR and its tributaries (Figure 2) (Stringfellow and Jain, 2010). While some streambeds, located outside of agricultural areas, run dry during the dry season, many tributaries receive flow almost exclusively during the dry season and summer flows are comprised almost entirely of irrigation return flows (Stringfellow et al., 2008c; Stringfellow and Jain, 2010; Gulati et al., 2013; Stringfellow et al., 2013).

The DWSC is a portion of the SJR between the City of Stockton and the confluence with the Sacramento River that has been dredged to allow for the navigation of ocean-going vessels to the Port of Stockton. The DO impairment addressed by this TMDL is located in the first 14 miles of the DWSC between the City of Stockton and Disappointment Slough (Figures 3 and 7) (Gowdy and Grober, 2003). Directly upstream of the DWSC, the RWCF discharges treated effluent from the City of Stockton into the SJR (Figure 7).

Data Collection and Measurements

Data were collected at over 50 locations in the SJR and SJR estuary and over 30 locations were included in the scientific monitoring program (Figure 5). Data collection was fully documented and collected according to strict quality assurance (QA) and quality control (QC) protocols. Details on analytical methods and QA/QC can be found in Report 4.1.2. Details on flow data collection and summary results for individual analysis are provided electronically as

Report 4.1.1, 4.2.2, and 4.2.3. Compiled final results of all analysis are provided as excel files (electronically).

Data Analysis

Detailed documentation of objectives, analysis of data, and interpretation of results for individual studies, tasks, and investigations conducted as part of the Estuary Project are provided in appendices following this synthesis report (Table 1). Detailed documentation of objectives, analysis of data, and interpretation of results for the Upstream Project are available from the EERP website (http://eerp.org/).

ENOD Calculation

According to the *Amendments to the Water Quality Control Plan for the Sacramento River and San Joaquin River Basins*, altered cross-sections of the San Joaquin River due to the construction of the DWSC and reduced flow in the San Joaquin River from upstream diversions contribute to the DO impairment (Gowdy and Grober, 2005). When the DO concentration is below regulatory standards, the excess net oxygen demand (ENOD) in lb day^{-1} is calculated by equation 1:

$$ENOD = \left(DO_{obj} - DO_{meas}\right) \times (Q_{DWSC} + 40) \times 5.4 \qquad (1)$$

where DO_{obj} is the DO criterion of 6 mg L^{-1} in the months of September through November and 5 mg L^{-1} during all other months, DO_{meas} is the measured DO concentration occurring in the SJR in mg L^{-1}, Q_{DWSC} is the net flow through the Stockton DWSC in cfs, 40 is an adjustment to account for flow measurement error, and 5.4 is a conversion factor. In this report, ENOD is reported as kg d^{-1}. A complete description of ENOD and ENOD calculations can be found in Report 4.8.5.

Results and Discussion

Mass balance and modeling studies were used to determine sources of ODS and their precursors (TMDL-need-A), investigate the growth and degradation mechanisms of ODS in transit through the SJR to the DWSC (TMDL-need-B) and to quantify the impact of different contributing factors on ENOD in the DWSC (TMDL-need-C). These studies are summarized in this report and complete results are presented in the appendices to this report. The details of the mass balance are presented in Report 4.8.3. The results of studies using the WARMF-2008 model to evaluate the growth and degradation mechanisms influencing ODS in transit from the source areas to the DWSC are presented in Report 4.8.1. Comparable studies with the WARMF-2012 model are presented in Report 4.8.2. An evaluation of the accuracy and precision of the WARMF-2008 and WARMF-2012 model results is presented in Report 4.8.8. The complete studies of the SJR estuary using the Link-Node model are presented in Report 4.8.5.

Sources of Oxygen Demanding Substances (ODS) and Their Precursors in the DO TMDL Source Area

All of the DO TMDL source area upstream of the tidal estuary drains past the Vernalis station on the SJR (Figures 5 and 7) and was accounted in both the mass balance analysis and WARMF modeling studies (Report 4.8.1, 4.8.2, and 4.8.3). A schematic chart showing all of the drains and tributaries entering the SJR that were included in these studies is presented in Figure 8. The sources draining directly to the estuary downstream of Vernalis typically contribute lower flows and mass loads than sources upstream of Vernalis. Sources directly entering the estuary downstream of Vernalis are accounted for in the Link-Node model studies (Report 4.8.5), discussed below.

Loads of ODS & ODS Precursors from the San Joaquin River to the Delta

The loads of ODS, ODS precursors, and salts entering the Delta from the SJR were evaluated using multiple approaches and can now be determined with certainty. Mass balance calculations show that over 600 million kilograms (kg) of total dissolved solids (TDS), 5.4 million kg of BOD, 50 thousand kg of chlorophyll-a, and 3.3 million kg of total nitrogen were discharged from the SJR to the Delta in 2007, a low flow year (Report 4.8.3). A comparison between the whole year and the summer irrigation season (April through September) shows that phytoplankton and BOD loads are higher in the summer, but nutrients are discharged from the watershed on a year-round basis (Table 2, see Report 4.8.3 for complete analysis). An analysis conducted using the WARMF-2008 model for the seven year period of October 1999 to September 2007, which included both low flow and high flow years, showed that annual loads of these constituents can be expected to be on average 1.5 times more than those observed in 2007 (Report 4.8.1). Using data collected from 2005 to 2007 as part of the Upstream Study and a daily-mean-load approach (Gulati et al., 2013), annual means loads of TDS, BOD, chlorophyll-a, and total nitrogen were over 800 million kg, 14 million kg, 89 thousand kg, and 1 million kg, respectively (Report 4.8.3). According to Gulati et al. (2013), the daily-load method has an expected accuracy of about 20%. A direct comparison (error analysis) between the loads at Vernalis calculated by the daily-load method and loads predicted by the WARMF-2008 model for the same time period gave a mean relative error of 10% and an absolute error of 32%, indicating the WARMF model has high precision and good accuracy (see Report 4.8.8 for complete analysis). The good agreement between direct measurements and model predictions indicate that the SJR has been sufficiently characterized and that the mass of materials entering the Delta from the SJR is as well characterized as possible for an open, dynamic system. The results indicate the WARMF-2008 model is a good tool for characterizing ODS and ODS precursor loads from the SJR to the Delta.

Sources of Loads of ODS & ODS Precursors to the San Joaquin River

The sources of loads of ODS and ODS precursors to the SJR upstream of Vernalis were determined using a mass balance approach (Report 4.8.3). The surface flows to and from the SJR are very well characterized in the region upstream of Vernalis and the mass balance for this region is of very high quality. Twenty-five drains, tributaries or diversions were identified as entering or exiting the SJR between Lander Avenue and Vernalis (Table 3, Figure 8) and a complete analysis of loading from each source can be found in Report 4.8.3.

Mass Balance for Total Dissolved Solids

Approximately two thirds (63.0%) of the TDS load at Vernalis was accounted for by surface water loads and a large proportion (37.0% annually) of the TDS mass load is attributed to groundwater flow into the river (Report 4.8.3). Mud Slough (20.9%), Salt Slough (20.3%), Tuolumne River (6.1%), Stanislaus River (5.1%), and Merced River (4.5%) were the greatest TDS contributors to the SJR.

Mass Balance for Biochemical Oxygen Demand

The Stanislaus River, Mud Slough, the Tuolumne River, and Salt Slough are the top contributors of BOD in the SJR (Report 4.8.3). Each of these sources can be expected to contribute over 0.5 million kg of BOD annually to the river. Together, they account for about 40% of the annual BOD load to the river (Report 4.8.3). However, on an annual basis, almost 40% more BOD load enters the Delta from the SJR than can be accounted for by tributary input, meaning there is a net production of BOD in the river upstream of Vernalis. During the irrigation season, over half of the BOD in the SJR at Vernalis is attributable to in-stream processes, such as the growth of phytoplankton in the river. Phytoplankton are an important source of BOD in this system and growth of phytoplankton in the river undoubtedly accounts for most of the increase in BOD, however, the increase is not proportional, as in-stream production of chlorophyll-a is approximately three times the value observed for the summation of the tributary inputs (Report 4.8.3). These results indicate that although BOD production by phytoplankton is very important, other sources or forms of BOD in the river should not be ignored.

Mass Balance for Phytoplankton

Sources of phytoplankton to the river were identified and quantitated (Report 4.8.3). Annually, the top contributors of chlorophyll-a to the river are Mud Slough, Salt Slough, SJR at Lander Avenue, and Los Banos Creek (Report 4.8.3). The major river tributaries (the Merced, Tuolumne, and Stanislaus Rivers) each contribute a smaller but significant load of chlorophyll-a to the SJR. During the irrigation season, the Merced River becomes proportionately more important than Los Banos Creek and the other tributary rivers as a source of phytoplankton load (Report 4.8.3). However, annually, the top four sources of load only contribute about 18% of the phytoplankton observed at Vernalis, with approximately 80% of the annual load and 90% of the irrigation season load of phytoplankton observed at Vernalis attributable to in-stream growth (Report 8.4.3). Since growth of phytoplankton in the river is a dynamic process, dependent on nutrients, light, flow, and other factors, as well as the seeding of phytoplankton into the river from the tributaries, the WARMF-2008 model was used to better understand how inputs of phytoplankton effect water quality outcomes as the SJR enters the Delta (Report 4.8.1). These dynamic processes are discussed in subsequent sections (addressing TMDL-need-B).

Mass Balance for Total Nitrogen

In 2007, the top five contributors of total nitrogen to the SJR were the Merced River, the Tuolumne River, Harding Drain, Westport Drain, and Mud Slough (Report 4.8.3). Together these sources accounted for approximately 80% of the annual nitrogen load in the river. The mass balance on total nitrogen suggests that groundwater is not a major contributor of nitrogen to the SJR (Report 4.8.3). This result is consistent with recent studies which found negligible nitrogen content in groundwater entering into the SJR (Zamora et al., 2012). The major form of nitrogen in the river is nitrate, but the mass balance shows that both ammonia-nitrogen and nitrate-nitrogen are contributing to phytoplankton growth in the river (Report 4.8.3).

In summary, the majors sources of ODS and ODS precursors to the SJR have been identified and quantified with accuracy, addressing the requirements of the DO TMDL under TMDL-need-A. Details of source identification, including a complete mass balance on the SJR, can be found in Report 4.8.1 and 4.8.3. Details concerning quality of data and accuracy of methods of calculating loads can be found in Report 4.1.1, 4.1.2, 4.2.1, and 4.8.4.

Growth or Degradation Mechanisms of ODS in Transit Through the Source Area to the DWSC

Eutrophication of the SJR has been identified as a major contributing factor to low DO conditions in the DWSC, as stated in the DO TMDL documentation (California Regional Water Quality Control Board Central Valley Region, 2005). Numerous studies have shown that phytoplankton grow rapidly in the main-stem of the SJR (e.g. Kratzer et al., 2004; Ohte et al., 2007; Stringfellow et al., 2009) and much evidence suggests that transport of ODS from upstream to the estuary is a contributing factor to low DO events in the DWSC (Lee and Jones-Lee, 2002; California Regional Water Quality Control Board Central Valley Region, 2005; Jassby and Nieuwenhuyse, 2005). Direct measurement, as discussed above, can identify sources of ODS (TMDL-need-A) and provide insight on fate and transport of ODS (TMDL-need-B), but models are needed to fully understand the fate and transport of ODS in the environment (TMDL-need-B and -C), due to the dynamic nature of processes governing how ODS results in oxygen depletion.

The WARMF-2008 model was developed as part of the Upstream Project to provide a tool for the Regional Board for management of the DO TMDL in the SJR (Herr et al., 2008; Stringfellow, 2008a; Stringfellow et al., 2008a). In the Estuary Project, the WARMF-2008 model was used to investigate the production and loss of ODS as a function of transit in the SJR (TMDL-need-B). The WARMF-2008 model was used to test the effect of nutrient control on ODS production (addressing TMDL-need-B), to identify individual sources of ODS to the river (TMDL-need-A), and to account for secondary effects of growth and transformation of ODS in the SJR between sources and discharge to the estuary (addressing TMDL-need-B). Details of the use of the WARMF-2008 model to assess the SJR, summarized here, can be found in Report 4.8.1.

Effect of Nutrient Loads on River Eutrophication

Model simulations were conducted to test the effect of nutrient loading in the SJR on phytoplankton growth and other water quality outcomes (Report 4.8.1). As discussed above, phytoplankton are a major cause of ODS in the SJR. Simulations were conducted to test the effect of removing nutrients individually or in combination on the loading of ODS and ODS precursors in the SJR (Report 4.8.1). Using the management alternatives function in the WARMF-2008 model consensus module, simulations were run with removal of all nutrient input simultaneously from all point and non-point sources. Ammonia, nitrate, and phosphate had various impacts on total phytoplankton when a single nutrient was removed. Ammonia had the greatest impact on reducing the total phytoplankton load, causing a reduction of 32%, whereas the removal of phosphate or nitrate only caused a reduction of 25% and 13%, respectively.

When ammonia or nitrate were removed in combination with phosphate, the reduction in total phytoplankton was between 30% and 37%, which is an improvement over nitrate removal alone, but not ammonia removal alone. The greatest reduction in phytoplankton occurred when all the sources of inorganic nitrogen were removed from the system. When nitrate and ammonia were removed together, the total phytoplankton observed at Vernalis decreased by 62%. Additional removal of phosphate with nitrogen sources did not achieve greater reductions in phytoplankton growth than nitrogen sources alone, suggesting that a nitrogen control program would have more effect on ODS production in the SJR than a phosphate control program.

The results of the simulations obtained with WARMF-2008 using the consensus module suggest that management actions directed at controlling phosphate discharges to the SJR are unlikely to be successful for controlling phytoplankton growth as a source of ODS, at least in part because of the storage of phosphate in river sediments. Restriction of nitrogen loading to the SJR is more likely to be an effective management strategy for phytoplankton derived ODS according to model simulations (see details in Report 4.8.1).

Management of nutrient loading to the SJR may be included in other TMDLs under consideration or development in the region (California Regional Water Quality Control Board Central Valley Region, 2009). For example, control of nitrate-nitrogen discharges to the river may be implemented in the SJR valley in the future as part of a salt management program (http://www.cvsalinity.org/). In the model simulations, significant level of nitrogen (over 80%) needed to be removed from the river to effect significant changes in phytoplankton loads at Vernalis (Report 4.8.1). Although this level of removal is extreme, it is not necessarily impossible, since most of the nitrogen in the river is in the form of nitrate (see Report 4.2.2 and 4.8.3). Engineered wetlands are being shown to be effective for removing nitrogen and other pollutants from agricultural drainage in the SJR watershed (Diaz *et al.*, 2010; O'Geen *et al.*, 2010; Diaz *et al.*, 2012; Karpuzcu and Stringfellow, 2012; Karpuzcu *et al.*, 2013; Stringfellow *et al.*, 2013). If properly engineered, widely implemented wetlands and other forms of nitrogen control in the SJR basin could have the additional effect of reducing ODS loads from the upstream SJR.

Sources of ODS, ODS Precursors, and Transformation of ODS in the SJR

The effects of removing loads from individual tributaries on the outcome of ODS loads at the Vernalis location on the SJR were tested to determine the relative importance of individual sources on ODS and ODS precursors (TMDL-need-A) and to measure the transformation of ODS from sources to the estuary (TMDL-need-B). Using the data module in the WARMF-2008 model, input files were modified one at a time to remove concentrations of pollutants without changing flow or river hydrology (see Report 4.8.1 for details). Results of the baseline simulation, which includes all inputs from all tributaries, were compared to simulations with inputs from individual tributaries removed, allowing the net impact of each source to be compared after inclusion of growth and degradation mechanisms occurring in the river. Results from this analysis were used to identify the major net sources of ODS and ODS precursors in the upstream area and allow for quantitative comparison of impacts from each sources, including accounting for river processes (Report 4.8.1).

Twelve tributaries (Salt Slough, Mud Slough, Los Banos Creek, Orestimba Creek, Harding Drain, Westport Drain, Del Puerto Creek, Ingram Creek, Hospital Creek, Merced River, Tuolumne River, and Stanislaus River) were tested using the WARMF-2008 model (Table 3, Figures 5 and 8). The three rivers (Merced River, Tuolumne River, and Stanislaus River) and three agricultural drainages (Salt Slough, Mud Slough, and Harding Drain,) were identified as contributing the most ODS and ODS precursors to the river.

Sources of Nutrients

The nutrients ammonia, nitrate, phosphate, and total phosphorous stimulate phytoplankton growth and are considered the major ODS precursors. The SJR exports approximately 8,700 kg nitrate-nitrogen, 650 kg ammonia-nitrogen, 14,000 kg total-nitrogen, and 1,800 kg total-phosphorous per day to the Delta (Report 4.8.3). No single drain or tributary was identified as a predominate source of ammonia-nitrogen, although removal of loads of ODS and ODS precursors from Ingram Creek, the Stanislaus River, and the Merced River reduced observed loads of ammonia at Vernalis by 2% to 5%. Interestingly, removal of loads from agricultural drains in the southern reaches of the study area resulted in increased ammonia-nitrogen loads at Vernalis (up to 10% collectively). The increase in ammonia load at Vernalis is caused by decreased in-stream phytoplankton uptake of ammonia, due to decreased phytoplankton growth when inputs of algae from southern tributaries are excluded (Report 4.8.1).

Most of the tributaries to the SJR contain significant concentrations of nitrate (Report 4.2.2). Comparisons between the WARMF-2008 baseline calculation and model scenarios with individual tributary loads removed indicate that reducing loads out of Mud Slough, the Tuolumne, and the Merced would have the greatest effect, reducing exports of nitrate from the SJR to the Delta by greater than 10% in each case (Report 4.8.1). Harding Drain, Salt Slough, the Stanislaus River, and Westport Drain have the effect of reducing nitrate by 4% to 8%, with the remaining drains having a less that 2% reductive effect (Report 4.8.1). Since nitrate is the predominant form of nitrogen in the SJR, trends for total-nitrogen follow trends for nitrate-nitrogen (Report 4.8.1).

Removal of loading from individual tributaries had only a small effect on the reduction of phosphate exports from the SJR to the Delta, according to model results (Report 4.8.1). These results agree with the results of the WARMF-2008 simulations conducted using the management alternatives function in the consensus module (discussed above) which did not show phosphate in-put as controlling phytoplankton growth in the river. These results are also consistent with the mass balance, which indicated that there is a significant storage of phosphorous in the river, presumable associated with sediments (Report 4.8.3). Out of all the tributaries, the removal of loads from Harding Drain caused the largest decrease in the export of reactive phosphate and total phosphorous with percent reductions of 10%, and 9%, respectively.

Harding Drain has typically had higher soluble phosphate concentrations than other drains (Report 4.2.2) and this higher concentration is traditionally attributed to discharges from regional municipal treatment facilities, however, the local municipal plant is not known to discharge to Harding Drain during the dry season (the effluent is used for irrigation instead of discharge), so it is not certain why phosphate concentrations remain high in the summer (Report 4.2.2 and 4.2.3).

<u>Sources of Oxygen Demanding Substances</u>

As discussed above, both organic and inorganic materials contribute oxygen demand in surface waters. Biochemical oxygen demand (BOD) is typically used as an indicative measurement of ODS, since BOD is the measurement of a reaction between ODS (e.g. organic matter and ammonia) and bacteria. For a more comprehensive understanding of the transformation of ODS in transit through the SJR and discharge to the Delta (TMDL-need-B), we need to examine not just BOD, but also DOC, organic-N, phytoplankton, and ammonia. Currently, the SJR exports approximately 41,000 kg BOD, 47,000 kg of DOC, 4,800 kg organic-nitrogen, 250 kg phytoplankton (as chlorophyll-a), and 650 kg ammonia-nitrogen to the Delta on average each day (Report 4.8.3). These are not independent variables, but rather interactive variables that provide a picture of ODS production and degradation mechanisms in transit through the source area to the DWSC (TMDL-need-B). Since ammonia concentration and loads are low compared to other ODS discharged from the SJR to the Delta, ammonia as an ODS in the SJR is not discussed at length in this synthesis report, but ammonia as ODS is included in analysis found in Report 4.8.1, 4.8.3, and 4.8.8. The effects of ammonia as ODS in the DWSC are discussed below and in Report 4.8.5.

By comparing the baseline scenario from the WARMF-2008 model to test scenarios in which loads, but not flows, are removed from individual tributaries, we can quantitate the effects of individual tributaries on ODS loads to the Delta, including an accounting for in-stream processes (Report 4.8.1). BOD, as calculated in the WARMF model, simulates the soluble carbonaceous BOD (CBOD). Oxygen demand from ammonia or organic nitrogen (nitrogenous BOD or NBOD) is calculated independently (Report 4.8.8). The results of the WARMF-2008 simulations show that, when accounting for in-stream processes, elimination of loads from the Tuolumne River, the SJR upstream of Lander Avenue., and the Merced River would reduce CBOD by 22%, 13%, and 10%, respectively. Removal of loads from the Stanislaus River, Mud Slough, and Salt Slough would each account for a 7% to 9% reduction in CBOD at Vernalis. Other tributaries have negligible effect on CBOD at Vernalis (< 3 %), according to model results (Report 4.8.1).

DOC and organic-nitrogen are created and destroyed by biological process. A complete description of the carbon and nitrogen cycles occurring in rivers is beyond to scope of this report, but growth of phytoplankton (primary production) tends to increase DOC and organic-nitrogen concentrations and microbial degradation (decay) can reduce DOC and organic-nitrogen concentrations. Not surprisingly, the sources identified in the model as most effecting CBOD also effect DOC and organic-nitrogen loads to the Delta (Report 4.8.1). DOC and organic-nitrogen are water quality constituents that contribute to BOD. The net accumulation of BOD, DOC, and organic-nitrogen are correlated with the growth of phytoplankton in the SJR (Report 4.8.1, 4.8.3).

Phytoplankton, which grow prolifically in the SJR, are a major source of organic carbon and organic nitrogen in the river, and are correlated with and contribute to BOD (Report 4.8.3). In modeling scenarios, the removal of loads, but not flows, from Salt Slough, Mud Slough, and Lander Avenue caused a reduction in phytoplankton load at Vernalis of 32%, 26%, and 27%, respectively. These effects were much greater than those observed by removing loads from any other source, which had impacts of less than 8% in all cases (Report 4.8.1). These results are consistent with mass balance studies (Report 4.8.3) and published literature that suggest that the three most southern tributaries (Salt Slough, Mud Slough, and Lander Avenue) inoculate the river with phytoplankton and these phytoplankton then grow rapidly in the abundant light and rich nutrients of the river (Ohte *et al.*, 2007; Stringfellow *et al.*, 2008c; Stringfellow *et al.*, 2009; Volkmar *et al.*, 2011).

In summary, growth and degradation mechanisms of ODS and ODS precursors from the point of discharge into the SJR, along the SJR, and into the DWSC and Delta have been fully characterized and described, addressing the requirements of the DO TMDL under TMDL-need-

B. Details of growth and degradation mechanisms can be found in Report 4.8.1. These results agree with observations from the mass balance (Report 4.8.3) and details concerning the precision and accuracy of model results can be found in Report 4.8.1, 4.8.2, 4.2.1, and 4.8.8. Phytoplankton growth has again been identified as a major component or type of ODS in the SJR system, but the results from this study suggest that ODS from sources other than phytoplankton growth do occur and contribute to the mass of ODS entering the estuary from the river.

The Impact of ODS on DO Concentrations in the DWSC Under a Range of Environmental Conditions

Downstream of Vernalis, the SJR becomes an estuary and is subject to tidal flows. The Vernalis location on the SJR is the legal limit of the Delta. The estuary portion of the SJR was investigated using the Link-Node model, which incorporates tidal hydraulics (Chen and Tsai, 2000; Chen, 2011). The Link-Node model was improved as part of the Estuary Project (Report 5.1.1) and the improved model was calibrated and published in May 2013 (the May_2013 model). The May_2013 Link-Node model was used to investigate the impact of ODS and ODS precursors on DO concentrations in the DWSC under a range of environmental conditions and considering the effects of chemical, biological, and physical mechanisms that add or remove dissolved oxygen from the water column in the DWSC (TMDL-need-C).

Link-Node Model Accuracy and Precision

The May_2013 Link-Node model was used to simulate hydrodynamics and water quality within the San Joaquin River estuary between Old River and Disappointment Slough (Figure 6) for the time period January 1, 2005 to December 31, 2011 (Report 4.8.5). The model results were compared to the observed data to determine the accuracy and precision of the model (Report 4.8.5). The accuracy (relative error) of the May_2013 model compared to measurements made at Rough & Ready Island (RRI) was -0.11 mg L^{-1}. The May_2013 model accuracy did not vary appreciably on a yearly or monthly basis (see Report 4.8.5). The precision (absolute error) of the May_2013 model was 0.90 mg L^{-1}. Overall, the May_2013 model tended to under-predict low DO events in comparison the Rough & Ready Island (RRI) measurements (see details in Report 4.8.5). DO violations were observed at RRI on 286 days (13%) during 2005-2011, as compared with 102 days (5%) predicted by the May_2013 model (Report 4.8.5). Although the May_2013 model may under predict low DO events, it is also possible that the RRI sensor may over-indicate low DO events. Investigation of DO conditions in the DWSC in the vicinity of the RRI monitoring station suggested that DO readings at RRI station tend to be lower than the surrounding water column (Report 4.8.6). Given the inherent uncertainties in both measurements and modeling, it is concluded that the 1-D Link-Node model is well suited for examining the relative effects of low flow, channel geometry, and the level or amount of ODS on low DO conditions in the DWSC (TMDL-need-C). This conclusion is consistent with previous studies evaluating DWSC models (Quinn et al., 2005; Jones and Stokes, 2006; Doyle et al., 2008; Monismith et al., 2008; Systech Water Resources Inc., 2008).

Impact of Contributing Factors to Low DO Conditions in the DWSC

In the Control Plan for the DO TMDL, the responsibility for low DO conditions in the DWSC was apportioned among several contributing factors according to an initial assessment (California Regional Water Quality Control Board Central Valley Region, 2005). Thirty-percent was apportioned to discharge, or effluent, from the City of Stockton Regional Wastewater Control Facility (RWCF). The RWCF effluent contained high concentrations of ammonia and in 2007 the RWCF upgraded facilities to include constructed wetlands and a nitrification system to remove ammonia and meet more stringent discharge standards. Sixty-percent of the responsibility was apportioned to nonpoint sources, which included discharges from irrigated land and those responsible for the maintenance of the DWSC. The apportionment to non-point sources included imports of ODS from the SJR to the Delta and DWSC, reduced flows due to diversions from the river and Delta, and changes in channel geometry to accommodate shipping and commercial activities. Ten-percent of the allocation was attributed to unknown or minor sources, which includes local inputs from urban sloughs and associated runoff from the City of Stockton and other communities bordering the DWSC.

In order to address TMDL-need-C, the improved Link-Node model was developed (Report 5.1.1) and used to investigate the impact of physical conditions and ODS on dissolved oxygen concentrations in the DWSC (Report 4.8.5). The complete investigation and analysis is discussed in detail in Report 4.8.5. In summary, a baseline scenario was created using the May_2013 Link-Node model to simulate the existing conditions without any changes to flow, channel geometry, or ODS inputs. This baseline scenario, was then compared to hypothetical management scenarios, in which a specific source of ODS or a contributing factor to low DO conditions (e.g. flow, channel geometry) was changed or eliminated. The number of hypothetical management scenarios that could be tested is very large. For example, any number of flow management scenarios could be examined or any range of changes on ODS inputs could be tested. The objective of the DO Estuary Project was not to test every possible scenario, but rather to further develop the Link-Node model and demonstrate the use of the model in the management of low DO conditions (Report 4.8.5 and 5.1.1). In this analysis, the utility of the improved Link-Node model for DO TMDL management was demonstrated by examining hypothetical management alternatives related to the original DO TMDL allocation (Report 4.8.5).

<u>Effect of Channel Geometry on Low DO Conditions in the DWSC</u>

To assess the impact that dredging and other changes to the geometry of the DWSC has on dissolved oxygen dynamics, the depth of Link-Node segments corresponding to the DWSC were changed (Figure 6). In the "No DWSC" scenario, the depth of these segments was reduced from approximately 40 feet to 12.5 feet, the depth of the natural stream channel upstream of the dredged area (Figures 9 and 10). Over all days, the model predicted that in the absence of the ship channel, mean concentration of DO would be 0.5 mg/L higher (Figure 9, Table 4). On days where the baseline model predicted DO concentrations would be below water quality objectives, the No DWSC scenario averaged 0.65 mg/L higher, according to model predictions (Table 5). The model further showed that ENOD, which is calculated only for days where DO concentrations were below water quality objectives, would improve by an average of 1,154 kg ENOD per day (Figure 10, Table 6).

Effect of ODS Imports from the SJR on Low DO Conditions in the DWSC

To assess the impact of loads of ODS from the SJR, the "No SJR" scenario tested the elimination of all ODS flowing into the Link-Node domain from the San Joaquin River (Figures 9 and 10). To estimate the impact of SJR inflows on dissolved oxygen concentrations in the DWSC, the concentrations of ODS in the Link-Node boundary inflow file were reduced to zero, but flows were not modified. ODS that were eliminated included BOD, ammonia-nitrogen, and phytoplankton (see Report 4.8.5 for details). Over all days, the model predicted that in the absence of inflows of ODS from the SJR upstream of the DWSC, mean concentrations of DO would be 0.66 mg/L higher (Figure 9, Table 4). At times when the baseline model predicted DO concentrations would be below water quality objectives, the No SJR scenario averaged 0.42 mg/L higher than the baseline model prediction (Table 5). The resultant change or improvement in ENOD was predicted to average 929 kg ENOD per day (Figure 10, Table 6).

Effect of Local ODS Inputs on Low DO Conditions in the DWSC

Elimination of all ODS flowing into the Link-Node domain from local, predominantly urban, tributaries was examined using the "No Tribs" scenario (Figures 9 and 10). The tributaries that were included in this scenario include 14-Mile Slough, Bear Creek, Mosher Slough, the Calaveras River, Mormon Slough, Duck Creek, Little John's Creek, French Camp Slough, Pixley Slough, and Stockton urban runoff which drains directly to the Delta (Figures 3, 5, and 6). To estimate the impact of tributary inflows on dissolved oxygen concentrations in the Delta, the concentrations of ODS in the Link-Node tributary inflow file were reduced to zero, but flows were not modified.

Examining DO concentrations over the entire period modeled (2005 to 2010), the model predicted that in the absence of local inputs of ODS, mean concentrations of DO would be 0.08 mg/L higher (Figure 9, Table 4). At times when the baseline model predicted DO concentrations would be below water quality objectives, the No Tribs scenario averaged 0.10 mg/L higher, according to model predictions (Table 5). The model further showed that ENOD would improve by 150 kg ENOD per day on average, calculated only for days where DO concentrations were below water quality objectives (Figure 10, Table 6).

Effect of ODS from the RWCF on Low DO Conditions in the DWSC

Elimination of all ODS flowing into the Link-Node domain from the City of Stockton Regional Wastewater Control Facility was examined using the "No RWCF" scenario (Report 4.8.5, Figures 9 and 10). The water chemistry of the Stockton RWCF was characterized using measured data provided in the Plant's discharge monitoring reports. To estimate the impact of RWCF inflows on DO concentrations, the concentrations of ODS in the RWCF inflow file were reduced to zero, but flows were not modified (see Report 4.8.5 for details).

Examining DO concentrations over the entire period modeled (2005 to 2010), the model predicted that in the absence of ODS inputs from the RWCF, mean concentrations of DO would be 0.10 mg/L higher (Figure 9, Table 4). At times when the baseline model predicted DO concentrations would be below water quality objectives, the No RWCF scenario averaged 0.25 mg/L higher, according to model predictions (Table 5). The model further showed that ENOD would improve by an average of 366 kg ENOD per day, calculated only where DO concentrations were below water quality objectives (Figure 10, Table 6). These results include effects of the RWCF both before and after improvements were made to control ammonia discharge to the river.

The effect of the installation of constructed wetlands and nitrification towers at the Stockton RWCF can be observed in the model output and by an examination of monitoring data. In Figure 9, the impact of potential improvements on DO concentration from the RWCF decreases after August 2007, when the nitrification system became fully operational. This effect is also shown in Figure 10, where the predicted effect of the RWCF on ENOD was much greater before the plant improvements. Although the average DO at RRI before and after installation of the nitrification facility were not significantly different (averaging 7.67±1.85 mg/L before and 7.59±1.54 mg/L after), the number of measurements below the DO criteria decreased following installation of the facility, from 10.5% of hourly observations before nitrification system installation to 6.2% after. Loads of ammonia-nitrogen and CBOD from the RWCF decreased after mid-2007 (Figures 11 and 12). Overall, it can be conclusively demonstrated that the impact of the RWCF is less now than it was before the installation and operation of the constructed wetlands and nitrification system and that the contribution of the RWCF to low DO conditions in the DWSC is significantly less now than it was prior to 2008.

Effect of Increasing Flows on Low DO Conditions in the DWSC

Flow has an important effect on DO concentrations in the DWSC. Flow from upstream brings ODS into the channel, which can cause low DO conditions, whereas high flows may flush the channel and prevent low DO conditions from developing. An almost infinite number of flow and ODS scenario combinations could be tested, but for this study, the model was tested using a scenario where flows were increased by 500 cfs (Flow+500) without any change in the water quality of the flows entering the DWSC. Increasing flows by 500 cfs is an increase in flow consistent with goals of the SJR restoration program (San Joaquin River Restoration Program, 2007). The Flow+500 scenario was used to simulate the effect of increased flow and was compared against the baseline scenario to evaluate whether increased flow in the DWSC would result in an improvement in DO and ENOD, in the absence of any change in water quality.

Examining DO concentrations over the entire period modeled (2005 to 2010), the model predicted that in the case of increasing flows by 500 cfs, every day, mean concentrations of DO would be 0.10 mg/L higher (Figure 13, Table 4). At times when the baseline model predicted DO concentrations would be below water quality objectives, the Flow+500 scenario averaged 0.39 mg/L higher, according to model predictions (Table 5). The model further showed that ENOD would improve by 513 kg ENOD per day on average, calculated only for days where DO concentrations were below water quality objectives (Figure 14, Table 6). Increasing flow by 500 cfs over baseline reduced the total number of DO excursions by 48% and reduced the total number of days with DO excursion by 39% (Report 4.8.5). According to model results, increasing flow will have the most beneficial effect during summer and fall, however at some times increasing flow by 500 cfs had a negative effect on DO concentrations. The model indicates that increasing flows may, on some days, aggravate the low DO conditions in the DWSC (Figure 13 and 14, Table 6). The negative effects of increasing flow are indicated by negative delta-ENOD values in Table 6, negative delta-DO values in Figure 13, and ENOD values above the Baseline value in Figure 14. This effect is probably due to the increased import of ODS with increased flows.

In previous studies, it was shown that when flows were above 3,000 cfs, low DO events did not occur. For example, a study of minimum daily DO concentrations as a function of flow for the November 1995 to September 2000 time period showed that when net flow through the DWSC exceeded 3000 cfs, DO did not fall below the applicable water quality criteria (California Regional Water Quality Control Board Central Valley Region, 2005). In this study, we examined the relationship between flow and DO concentration for January 2005 to December 2011 and found that DO objectives were met when flows were above 3,000 cfs, with the exception of one violation on August 17, 2005 (Figure 15). However, increasing flow in the DWSC to this level is unlikely to be a practical management alternative for low DO conditions.

Comparison of Management Scenarios

The predicted effects of the different identified variables on overall DO concentrations in the DWSC are summarized in Table 4. Based on the predicted effect of each remediation scenario on DO concentrations, the No SJR scenario results in the most improvement in mean DO concentration (0.66 mg/L), followed by No DWSC (0.50 mg/L), with the effect of the No Trib, the No RWCF, and the Flow+500 scenarios approximately equal (0.08, 0.10, and 0.10 mg/L, respectively). However, overall model results for the effect of the different parameters on the minimum DO concentration suggest that increasing flow would have more effect (0.27 mg/L DO) than the DWSC (0.11 mg/L), the urban tributaries (0.10 mg/L), the municipal discharge (0.08 mg/L), or the SJR (0.07 mg/L).

The timing of impact is important and even if overall conditions improve, the river is only considered impacted when the DO concentration falls below the water quality criteria (California Regional Water Quality Control Board Central Valley Region, 2005, 2009). An analysis of model output for periods when DO concentrations were below the water quality criteria are presented in Table 5. When only considering days when the baseline scenario predicted DO concentrations would be below the water quality objectives, the DWSC is predicted to have a proportionally larger effect on mean DO concentrations (a 0.65 mg/L improvement in DO concentration) than removing ODS from the SJR (a 0.42 mg/L improvement) or increasing flows (a 0.39 mg/L improvement). Both the No RWCF and the No Tribs scenario had much less effect (0.25 mg/L and 0.10 mg/L, respectively). The current effect of the RWCF is actually lower, since this analysis includes the impact from 2005 to 2007, before the plant up-grade in 2007. Examining the effect on minimum DO concentrations, the model suggests the effect of the DWSC on minimum observed DO concentrations (0.33 mg/L) could be three times the effect of any other scenario tested (≤ 0.10 mg/L), except the Flow+500 scenario (0.27 mg/L). The apparent importance of the DWSC in relation to the other parameters is due, in part, to the seasonal occurrence of low DO conditions in the summer, when flows from the SJR and urban runoff are minimized (Figure 9). Increasing flows by 500 cfs would offer overall improvement, but as discussed above, in some cases increasing flows would have a negative effect (Figure 13) and the timing of those effects could correspond to the July to December fall-run salmon migration periods (see 2007 in Figure 13).

By definition, the assimilative capacity of the river has been exceeded when the ambient DO concentration falls below the DO water quality objectives. In the DO TMDL control plan, ENOD is used as a quantitative assessment of how much the assimilative capacity of the river, at the DWSC, has been exceeded (California Regional Water Quality Control Board Central Valley Region, 2005, 2009). The intention of the ENOD is to establish relationship between the DO concentration and the mass of oxygen that would be required, for example by mechanical aeration, to bring the DO concentration back up to the water quality criteria. Comparison of how each factor influences ENOD also indicates that the geometry of the DWSC and the import of ODS from the SJR have the most negative effect on DO in the DWSC (Table 6). When examining the mass deficit of DO, as ENDO, the effect of the RWCF and the urban tributaries is less than one-third the effect of the DWSC geometry and ODS imports from the SJR (Table 6). The effect of increasing flow on ENOD is complicated by the positive relationship between flow and ODS load in this scenario, but it is apparent that increasing flow by 500 cfs is not in the same order of impact as the DWSC or the import of ODS from upstream.

It should be noted that model results indicate that no single factor alone, if resolved or eliminated, would bring the river into compliance with DO water quality objectives all the time. This result is visible in Figure 10, during 2009, when no model scenarios results in a positive ENOD, indicating that in all cases the river assimilative capacity still is exceeded. The assimilative capacity of the river is considered restored if the ENOD falls below the x-axis (becomes negative) in Figure 10. These results indicate that multiple factors will need to be mitigated to avoid exceeding the assimilative capacity of the river at all times.

Apportionment of ENOD Among Contributing Factors

In the DO TMDL Control Plan, the responsibility for ENOD is apportioned among the contributing factors according to an initial assessment, where 30 percent was apportioned to discharge or effluent from the City of Stockton Regional Wastewater Control Facility; 60 percent to nonpoint sources, which include discharges from irrigated land and those responsible for the maintenance of the DWSC; and 10 percent from unknown or minor sources (California Regional Water Quality Control Board Central Valley Region, 2009). Installation of the nitrification system at the City of Stockton RWCF has demonstrably been an effective in reducing the ODS load from the facility (Figures 11 and 12) and local tributaries cannot be shown as having a large influence based on model results (Tables 4, 5, and 6). The relative contribution of the DWSC to ENOD appears to be greater than the contribution from the import of ODS from the SJR, despite the fact that overall the SJR is responsible for large loads of ODS to the DWSC. This result is due to the occurrence of low DO conditions in the DWSC during periods when flows, and therefore imports of ODS from upstream sources are low. The results of the Estuary Study suggest that the apportionment of responsibility between contributing factors may need to be adjusted.

In summary, the Link-Node model was used to investigate the impact of ODS on DO concentrations in the DWSC under a range of environmental conditions, including changes in the physical conditions of channel geometry and flow (TMDL-need-C). Details of the Link-Node improvement and calibration can be found in Report 5.1.1. Detailed analysis of the precision and accuracy of the Link-Node model can be found in Report 4.8.5. Supplementary information concerning the accuracy of DO measurements and the relationship between continuous monitoring locations and DO throughout the DWSC can be found in Report 4.8.6.

Using the Integrated WARMF Link-Node Model

The newer version of the SJR-WARMF model (WARMF-2012), which includes increased functionality of the landuse component, allowing simulation of subwatershed inputs to the SJR, was tested as part of this project (Report 5.2.1, 5.2.2, and 5.2.3). The WARMF-2012 version includes the improved and calibrated Link-Node model (May_2013). The integrated

WARMF and Link-Node model calculates loads from individual tributaries or sources to the DWSC without running separate scenarios, as was done for the WARMF-2008 and Link-Node analysis discussed above. Since landuse functionality is included in the WARMF-2012 model, the individual watersheds were examined and calibrated as part of this project (Report 5.2.1, 5.2.2, and 5.2.3) and the improved calibrations on individual tributaries are included in the current version of the WARMF model (available at http://www.systechengineering.com/). Investigation of the effects of tributary loads using the WARMF-2012 model was conducted as part of this study.

A load simulation in the WARMF 2012 model was conducted by Systech Water Resources and results were delivered to EERP for analysis. The results are in the form of an allocated sum attributable to each tributary or point source, referred to as a "Gowdy output," which accounts for initial loads to the river and the growth and decay processes that occur between the source and the DWSC (see Report 4.8.2 for details). Gowdy output results for CBOD, total phytoplankton, and ammonia from sources along the main stem of the San Joaquin River for the time period January 1, 2005 through September 30, 2012 were provided on a daily time step. The output is described in detail in Report 4.8.2.

Results from the WARMF-2012 model suggest that the top five sources for soluble CBOD contributed 89.3% of the total BOD load. These sources were identified as the Tuolumne River, the SJR above Lander Avenue, the Merced River, Los Banos Creek (which included Mud Slough in the WARMF-2012 model) and the Stanislaus River. The Tuolumne River contributed the most soluble CBOD at 15,745,399 kg (25.8%) of the total load and the Stanislaus River contributed the fifth highest soluble CBOD at 7,528,286 kg (12.3%) of the total load to the SJR estuary.

The top five sources for soluble CBOD were also the top five sources for total phytoplankton, but in a different order. According to the WARMF-2012 model, the San Joaquin River at Lander Avenue had the largest contribution of total phytoplankton, with 153,256 kg chlorophyll-*a* (44.8%) of the total load, while the Stanislaus River had the fifth largest contribution of 21,292 kg chlorophyll-*a* (6.4%) of the total load. The top five sources for ammonia consisted of 62.4% of the total load; the Tuolumne River had the highest load of 286,168 kg (17.2%) while the Merced River has the fifth highest load of 137,608 kg (8.3%). The model results suggest that, while there were only a few BOD and phytoplankton sources contributing to the majority of the total load, there were a number of ammonia sources that each contribute a small amount of the total load. The top five ammonia sources included the City of Modesto Water Quality Control Facility, with the fourth highest ammonia contribution.

There was limited overlap between the WARMF-2008 and the WARMF-2012 simulation periods, but results lacked agreement on individual source contributions and the combined loads from the 2008 model were consistently larger than the 2012 model. One explanation of the difference is that the models were run on different time steps. It was observed that loads calculated from the same model coefficients on different time steps were different, but had consistent trends between values. Another possible source of difference between the two models is the differences in the spatial scope of the analysis, as the 2012 model domain is larger than the 2008 model domain. This may result in in-stream processes in the 2012 model having a larger effect than in the 2008 model.

Summary & Conclusions

The scientific studies required by the DO TMDL have been completed. The DO TMDL (California Regional Water Quality Control Board Central Valley Region, 1998, 2005, 2009) required that studies must be conducted to

(i) identify and quantify sources of oxygen demanding substances and their precursors in the dissolved oxygen TMDL source area (TMDL-need-A);

(ii) determine growth or degradation mechanisms of these oxygen demanding substances in transit through the source area to the DWSC (TMDL-need-B); and

(iii) investigate the impact of these oxygen demanding substances on dissolved oxygen concentrations in the DWSC under a range of environmental conditions and considering the effects of chemical, biological, and physical mechanisms that add or remove dissolved oxygen from the water column in the DWSC (TMDL-need-C).

In this report, the results of prior studies were summarized and the results of the current studies conducted to meet the requirements of the DO TMDL are presented and discussed in the context of the DO TMDL study objectives.

The results of direct measurements and modeling with the WARMF-2008 and WARMF-2012 models indicate that tributaries in the southern portion of the study area (Figure 5) contribute a disproportionate amount of ODS compared to flows. Salt Slough and Mud Slough are particularly identified as contributing phytoplankton, which then grow in the river and cause an impact in excess of the original discharge of ODS from the sloughs (Table 3). However, both the modeling and mass balance results indicate that phytoplankton are only one component of ODS in the SJR and that other materials, such as soluble organic carbon and ammonia- nitrogen, are contributing ODS to the river. All analyses indicated that the three east-side rivers, the Merced, Tuolumne, and Stanislaus Rivers, are important sources of ODS to the SJR. Ammonia-nitrogen discharges are an important ODS source, but ammonia-nitrogen is also an ODS precursors that contributes to ODS by stimulating phytoplankton growth in the river. Both model results and the mass balance suggest ammonia-nitrogen is important to the stimulation of phytoplankton growth, but nitrate is also an important source of nitrogen causing eutrophication.

Model results indicate that reducing nitrogen discharge to the river from drains and tributaries would reduce eutrophication, if significant reductions in nitrogen load can be achieved. The model also indicated a lesser, but still positive, effect from the reduction of phosphorous discharges to the river. Phosphorous is entering the SJR from many sources, although Harding Drain contributes the most phosphorous from a single drainage. Modeling suggests that the implementation of a phosphate control plan was a less effective approach for the control of eutrophication than nitrogen control, in part because large amounts of phosphate are apparently stored in the SJR or may be entering the river with groundwater flows. In contrast, the mass balance and modeling indicate nitrogen loads to the river are from surface-water, not groundwater, and there is little storage of nitrogen in the river. In addition, it has been shown that constructed wetlands are a proven technology for the removal of nitrogen from agricultural drainage and other surface waters, further supporting the concept of a nitrogen control plan for the control of eutrophication in the SJR.

The Link-Node component of the integrated watershed model was improved and calibrated. It was demonstrated that a 1-D model was sufficient to model the DWSC, confirming the results of prior studies. The Link-Node model was used to explore and delineate the root causes of low DO conditions in the DWSC. The Link-Node model was used to simulate the effect of five model scenarios: (i) DWSC geometry changes so oxygen depletion is removed, (ii) oxygen depleting loads from the RWCF removed, (iii) oxygen depleting loads removed from the upstream San Joaquin River, (iv) oxygen depleting loads from urban tributaries removed, and (v) increasing flows by 500 cfs. The results of this analysis suggest that the apportionment of responsibility between contributing factors may need to be adjusted compared with what was previously established. Installation of constructed wetlands and the nitrification system at the City of Stockton Regional Wastewater Control Facility has been effective in reducing the ODS load from the facility. Local (mostly urban) tributaries cannot be shown as having a large influence based on model results. The relative contribution of the DWSC geometry to ENOD appears to be greater than the contribution from the import of ODS from the SJR, despite the fact that overall the SJR is responsible for large loads of ODS to the DWSC. This result is due to the occurrence of low DO conditions in the DWSC during periods when flows, and therefore imports from upstream, are low.

Model results demonstrated that removing any one factor would not resolve the low DO problem in entirety, indicating that a multifaceted approach will be needed to avoid exceeding the carrying capacity of the river at the DWSC. These results indicate that mitigating low DO problems in the estuary will require an ecosystem level approach, rather than managing water quality by individual constituents, due to the complex interactions between multiple variables that result in low DO outcomes. Increasing the overall health of the river system, by restoring riparian functionality, improving flows, reducing pollutant loads, and improving water quality, will have a greater beneficial effect on DO concentrations in the estuary than any one action taken alone. A regulatory approach utilizing watershed level environmental management, rather than management focused on individual constituents, is now being implemented in the European Union to guide activities for the improvement of impaired waterbodies.

Finally, the newest version of the SJR-WARMF model (called here WARMF-2012), which includes increased functionality of the landuse component and the improved Link-Node model, was used to simulate output from tributary (diffuse) sources and point sources to the DWSC. The results, in the form of an allocated sum attributable to each tributary or point sources, were subject to analysis. The model results suggest that the top five sources for BOD contributed 89.3% of the total BOD load. These sources were identified as the Tuolumne River, the SJR above Lander Avenue, the Merced River, Los Banos Creek (which included Mud Slough in the WARMF-2012 model), and the Stanislaus River. The WARMF-2012 results support the results of the WARMF-2008 model and the mass balance in that they identify the same watersheds as major contributors of ODS and ODS precursors to the SJR. The WARMF-2008 model and the Link-Node May_2013 version were specifically developed for the DO TMDL and it is recommended that these models continued to be used for management of DO in the SJR until the landuse functions in the more advanced, integrated versions of WARMF (e.g. WARMF-2012) are specifically calibrated for the watersheds in the DO TMDL source area.

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References

Bain, R.D., McCarty, P.L., Robertson, J.A., Pierce, W.H., 1970. Effects of an Oxidation Pond Effluent on Receiving Waters in the San Joaquin River Estuary. June. University of Kansas,

Balls, P.W., Brockie, N., Dobson, J., Johnston, W., 1996. Dissolved oxygen and nitrification in the upper Forth estuary during summer (1982-92): Patterns and trends. Estuarine Coastal and Shelf Science 42, 117-134.

Breitburg, D.L., Adamack, A., Rose, K.A., Kolesar, S.E., Decker, M.B., Purcell, J.E., Keister, J.E., Cowan, J.H., 2003. The pattern and influence of low dissolved oxygen in the Patuxent River, a seasonally hypoxic estuary. Estuaries 26, 280-297.

Bricker, S.B., Longstaf, B., Dennison, W., Jones, A., Boicourt, K., Wicks, C., Woerner, J., 2008. Effects of nutrient enrichment in the nation's estuaries: A decade of change. Harmful Algae 8, 21-32.

California Department of Water Resources, 2001. Methodology for Flow and Salinity Estimates in the Sacramento-San Joaquin Delta and Suisun Marsh, 22nd Annual Progress Report to the State Water Resources Control Board in Accordance with Water Right Decision 1485, Order 9. California Department of Water Resources, Sacramento, CA.

California Department of Water Resources, 2013. Methodology for Flow and Salinity Estimates in the Sacramento-San Joaquin Delta and Suisun Marsh 34th Annual Progress Report to the State Water Resources Control Board in Accordance with Water Right Decisions 1485 and 1641. June. California Department of Water Resources, Sacramento, CA.

California Regional Water Quality Control Board Central Valley Region, 1998. Water Quality Control Plan (Basin Plan) for the Sacramento and San Joaquin River Basins (4th Edition). September 15. California Environmental Protection Agency, Central Valley Regional Water Quality Control Board, Rancho Cordova, CA.

California Regional Water Quality Control Board Central Valley Region, 2005. Amendments to the Water Quality Control Plan for the Sacramento River and San Joaquin River Basins for the Control Program for Factors Contributing to the Dissolved Oxygen Impairment in the Stockton Deep Water Ship Channel. Feburary 28. California Environmental Protection Agency, Central Valley Regional Water Quality Control Board, Rancho Cordova, CA.

California Regional Water Quality Control Board Central Valley Region, 2009. The Water Quality Control Plan (Basin Plan) for the California Regional Water Quality Control Board Central Valley Region, 4th Edition, Revised September 2009 (with Approved Amendments), The Sacramento River Basin and the San Joaquin River Basin, 4 ed. California Regional Water Quality Control Board Central Valley Region, Sacramento, CA.

Chen, C.W., Tsai, W., 2000. Rough Loading Calculation for Dissolved Oxygen Sinks In Lower San Joaquin River. Systech Engineering, Inc.,

Chen, C.W., Tsai, W., 2002. Improvements and Calibrations of Lower San Joaquin River DO Model, Final Report for CALFED Grant 99-B16, and DWR 4600000989. Systech Engineering, Inc., San Ramon, CA.

Chen, C.W., 2011. Framework to Determine Total Maximum Daily Flow Diversions for Fish Protection. Journal of Environmental Engineering-ASCE 137, 1099-1102.

Diaz, F.J., O'Geen, A.T., Dahlgren, R.A., 2010. Efficacy of constructed wetlands for removal of bacterial contamination from agricultural return flows. Agric. Water Manage. 97, 1813-1821.

Diaz, F.J., O'Geen, A.T., Dahlgren, R.A., 2012. Agricultural pollutant removal by constructed wetlands: Implications for water management and design. Agric. Water Manage. 104, 171-183.

Doyle, L., Fleenor, W., Schladow, S.G., Monismith, S., Hench, J., Smith, P., Rueda, F., 2008. An Application of the SI3DWQ Hydrodynamics and Water Quality Model to the Stockton Deep Water Ship Channel. May. University of California Davis, Davis, CA.

Foe, C., Gowdy, M., McCarthy, M., 2002. Draft Strawman Allocation of Responsibility Report. January. California Regional Water Quality Control Board Central Valley Region, Rancho Cordova, CA.

Gowdy, M.J., Grober, L.F., 2003. Total Maximumm Daily Load for Low Dissolved Oxygen in the San Joaquin River. Regional Water Quality Control Board Central Valley Region, Sacramento, CA.

Gulati, S., Stubblefield, A.A., Hanlon, J.S., Spier, C.L., Stringfellow, W.T., 2013. Use of continuous and grab sample data for calculating total maximum daily load (TMDL) in agricultural watersheds. Chemosphere in press.

Hall, L.W., Anderson, R.D., 2003. Parametric and probabilistic analysis of historical chlorpyrifos surface water monitoring data from the San Joaquin River watershed: 1991-2001. Water Air and Soil Pollution 150, 275-298.

Herr, J., Chen, C., 2006a. San Joaquin River Model Calibration Report. A Deliverable for CALFED Propject ERP-02D-P63 Monitoring and Investigations for the San Joaquin River and Tributaries Related to Dissolved Oxygen. Task 6 Model Calibration and Forecasting. December 11. Systech Engineering, Inc., San Ramon, CA.

Herr, J., Chen, C., Werkhoven, K.v., 2008a. Final Report for the Task 6 Modeling of the San Joaquin River. A Deliverable for CALFED Propject ERP-02D-P63 Monitoring and Investigations for the San Joaquin River and Tributaries Related to Dissolved Oxygen.

Task 6 Model Calibration and Forecasting Systech Water Resources, Inc., Walnut Creek, CA.

Herr, J., Chen, C., Werkhoven, K.v., 2008b. Final Report for the Task 6 Modeling of the San Joaquin River. A Deliverable for CALFED Propject ERP-02D-P63 Monitoring and Investigations for the San Joaquin River and Tributaries Related to Dissolved Oxygen. Task 6 Model Calibration and Forecasting. Systech Water Resources, Inc., Walnut Creek, CA.

Herr, J., Chen, C.W., 2006b. Annual Report for the Task 6 Modeling of the San Joaquin River: Documentation Report. November 17. Systech Engineering, Inc., San Ramon, CA.

Herr, J.W., Chen, C.W., 2007. San Joaquin River Upstream DO TMDL Project ERP - 02D - P63 Task 6: Modeling Study Forecasting Results Report. November 15. Systech Engineering, Inc., San Ramon, CA.

Herr, J.W., Chen, C.W., 2012. WARMF: Model use, calibration, and validation. Transactions of the Asabe 55, 1385-1394.

HydroQual, 2006. San Joaquin River Dissolved Oxygen Depletion Model, Task 4 Final Report, 3D San Joaquin River Water Quality Calibration 2000 - 2001. May. HydroQual, Mahwah, NJ.

Jassby, A., Nieuwenhuyse, E.E.V., 2005. Low dissolved oxygen in an estuarine channel (San Joaquin River, California): mechanisms and models based on long-term time series. San Francisco Estuary and Watershed Science Vol.3, Issue 2, Article 3. (http://www.estuaryandwatershedscience.org).

Jassby, A.D., 2005. Phytoplankton Regulation in a Eutrophic Tidal River (San Joaquin River, California). San Francisco Estuary and Watershed Science. Vol. 3, Issue 1, Article 3. (http://www.estuaryandwatershedscience.org).

Jones and Stokes, 2006. Proposed Uses of DWSC Water Quality Models During Implementation of the San Joaquin River Dissolved Oxygen Total Maximum Daily Load. June. Jones & Stokes, Sacramento, CA.

Karpuzcu, M.E., Stringfellow, W.T., 2012. Kinetics of nitrate removal in wetlands receiving agricultural drainage. Ecological Engineering 42, 295-303.

Karpuzcu, M.E., Sedlak, D.L., Stringfellow, W.T., 2013. Biotransformation of chlorpyrifos in riparian wetlands in agricultural watersheds: Implications for wetland management. Journal of Hazardous Materials 244, 111-120.

Keller, A., 2000. Peer Review of the Watershed Analysis Risk Management Framework (WARMF) – An evaluation of WARMF for TMDL applications by independent experts using USEPA guidelines, Technical Report 2000.1000252. Electric Power Research Institute, Palo Alto, CA.

Kratzer, C.R., Dileanis, P.D., Zamora, C., Silva, S.R., Kendall, C., Bergamaschi, B.A., Dahlgren, R.A., 2004. Sources and Transport of Nutrients, Organic Carbon, and Chlorophyll-a in the San Joaquin River Upstream of Vernalis, California, during Summer and Fall, 2000 and 2001, Report Number 2003-4127. US Geological Survey Information Services, Denver, CO.

Kratzer, C.R., Kent, R.H., Saleh, D.K., Knifong, D.L., Dileanis, P.D., Orlando, J.L., 2011. Trends in nutrient concentrations, loads, and yields in streams in the Sacramento, San Joaquin, and Santa Ana Basins, California, 1975–2004: U.S. Geological Survey Scientific Investigations Report 2010-5228. U.S. Department of the Interior, U.S. Geological Survey, Reston, Virginia.

Larry Walker & Associates, Luhdorff & Scalmanini Consulting Engineers, Systech Water Resources, NewFields Agriculture and Environmental Resources, 2010. Salt and Nitrate Sources Pilot Implementation Study Report. A Deliverable for the Central Valley Salinity Coalition. Larry Walker & Associates, Davis, CA.

Lee, G.F., Jones-Lee, A., 2003. Synthesis and Discussion of Findings on the Causes and Factors Influencing Low DO in the San Joaquin River Deep Water Ship Channel near Stockton, CA: Including 2002 Data. Report Submitted to SJR DO TMDL Steering Committee/Technical Advisory Committee and CALFED Bay-Delta Program. May. G. Fred Lee and Associates, El Macero, CA.

Lehman, P., 2001. The Contribution of Algal Biomass to Oxygen Demand in the San Joaquin River Deep Water Channel, Final Draft Report, San Joaquin River Dissolved Oxygen TMDL Steering Committee. California Department of Water Resources Sacramento, CA.

Lehman, P.W., 1992. Environmental-Factors Associated with Long-Term Changes in Chlorophyll Concentration in the Sacramento-San-Joaquin Delta and Suisun Bay, California. Estuaries 15, 335-348.

Lehman, P.W., Sevier, J., Giulianotti, J., Johnson, M., 2004. Sources of oxygen demand in the lower San Joaquin River, California. Estuaries 27, 405-418.

Leland, H.V., Brown, L.R., Mueller, D.K., 2001. Distribution of algae in the San Joaquin River, California, in relation to nutrient supply, salinity and other environmental factors. Freshwater Biology 46, 1139-1167.

Lin, Z.Q., Cervinka, V., Pickering, I.J., Zayed, A., Terry, N., 2002. Managing selenium-contaminated agricultural drainage water by the integrated on-farm drainage management system: role of selenium volatilization. Water Research 36, 3150-3160.

Litton, G.M., Brunell, M., Monroe, J.C., Quinn, N.W.T., 2008. San Joaquin River Upstream DO TMDL Project ERP-02D-P63 Task 8 Final Report: Linking the San Joaquin River to the Stockton Deep Water Ship Channel. April 17. Civil Engineering Department, Department of Biology, University of the Pacific and Ecology Department, Lawrence-Berkeley National Laboratory, Stockton, CA.

Litton, G.M., Brunell, M., Quinn, N.W.T., Monroe, J.C., 2007. San Joaquin River Upstream DO TMDL Project (ERP-02D-P63) Task 8: Linking the San Joaquin River to the Stockton Deep Water Ship Channel Interim Task Report #3. May 15. Civil Engineering Department, University of the Pacific, Stockton, CA.

McCarty, P.L., 1969. An Evaluation of Algal Decomposition in the San Joaquin Estuary (Research grant DI-16010 DL). December 19. Federal Water Pollution Control Administration, Washington, DC.

Monismith, S., Hench, J., Smith, P., Fleenor, W., Doyle, L., Schladow, S.G., 2008. An Application of the SI3D Hydrodynamics Model to the Stockton Deep Water Ship Channel: Physics and Model Application. May. Stanford University, Stanford, CA.

O'Geen, A.T., Budd, R., Gan, J., Maynard, J.J., Parikh, S.J., Dahlgren, R.A., 2010. Mitigating Nonpoint Source Pollution in Agriculture with Constructed and Restored Wetlands. Advances in Agronomy, Vol 108, pp. 1-76.

Ohte, N., Dahlgren, R.A., Silva, S.R., Kendall, C., Kratzer, C.R., Doctor, D.H., 2007. Sources and transport of algae and nutrients in a Californian river in a semi-arid climate. Freshwater Biology 52, 2476-2493.

Quinn, N.W.T., Jacobs, K., Chen, C.W., Stringfellow, W.T., 2005. Elements of a decision support system for real-time management of dissolved oxygen in the San Joaquin River Deep Water Ship Channel. Environmental Modelling & Software 20, 1495-1504.

Rabalais, N.N., Turner, R.E., Wiseman, W.J., 2002. Gulf of Mexico hypoxia, aka "The dead zone". Annual Review of Ecology and Systematics 33, 235-263.

Saleh, D.K., Domagalski, J.L., Kratzer, C.R., Knifong, D.L., 2007. Organic Carbon Trends, Loads, and Yields to the Sacramento-San Joaquin Delta, California, Water Years 1980 to 2000, Water Resources Investigation Report 03-4070, Second Edition. US Geological Survey, Sacramento, California.

San Joaquin River Restoration Program, 2007. Implementing the Stipulation of Settlement in NATURAL RESOURCES DEFENSE COUNCIL, et al., v. KIRK RODGERS, UNITED STATES BUREAU OF RECLAMATION, et al., Case No. S-88-1658-LKK/GGH UNITED STATES DISTRICT COURT, Program Management Plan. Natural Resources Defense Council, Sacramento, CA. (http://www.restoresjr.net/).

Shields, E., Weidman, C., 2008. A Quantitative Approach to Characterizing Hypoxic Events. Journal of Coastal Research, 50-58.

Stringfellow, W., 2008a. San Joaquin River Upstream DO TMDL Project ERP - 02D - P63 Task 12: DO Project Final Report. June. San Joaquin Valley Drainage Authority & University of the Pacific Ecological Engineering Research Program, Stockton, CA.

Stringfellow, W.T., 2008b. Ranking methods to set restoration and remediation priorities on a watershed scale. Water Science and Technology 58, 2025-2030.

Stringfellow, W.T., 2008c. Ranking tributaries for setting remediation priorities in a TMDL context. Chemosphere 71, 1895-1908.

Stringfellow, W.T., McGahan, J.C., Ploss, L., Brown, R., Chen, C.W., Kendall, C., Quinn, N.W.T., Litton, G., Borglin, S.E., Nader, P., Rajbhandari, H.L., Dahlgren, R., Sebasto, T., Jacobs, K., 2003. Monitoring and Investigations of the San Joaquin River and Tributaries Related to Dissolved Oxygen. March. Environmental Engineering Research Program, University of the Pacific, Stockton, CA.

Stringfellow, W., Brown, R., Dahlgren, R., Goudy, M., LaBay, J., Litton, G., Siegel, S., Marcotte, B., 2007a. Low Dissolved Oxygen Conceptual Model Delta Regional Ecosystem Restoration Implementation Plan (DERRIP) Peer Review Draft. June 8. Wetlands and Water Resources, San Francisco, CA.

Stringfellow, W.T., Borglin, S.E., Dahlgren, R., Hanlon, J.S., Graham, J., Burkes, R., Hutchinson, K., 2007b. San Joaquin River Upstream DO TMDL Project (ERP - 02D - P63) Task 4: Monitoring Study Interim Task Report # 3. Ernest Orlando Lawrence Berkeley National Laboratory Formal Report No. LBNL-63243. March 31, 2007. Lawrence Berkeley National Laboratory & The University of the Pacific, Berkeley, CA.

Stringfellow, W., Borglin, S., Hanlon, J., Graham, J., Burks, R., 2008a. Scientific Studies Supporting Development of a Dissolved Oxygen TMDL. Water Practice 2, 1-10.

Stringfellow, W., Borglin, S., Hanlon, J., Graham, J., Dahlgren, R., Burkes, R., Spier, C., Letain, T., Hutchison, K., Granadosin, A., 2008b. San Joaquin River Upstream DO TMDL Project ERP - 02D - P63 Task 4 Final Report: Monitoring Study. May. University of the Pacific, Stockton, CA.

Stringfellow, W.T., Hanlon, J.S., Borglin, S.E., Quinn, N.W.T., 2008c. Comparison of wetland and agriculture drainage as sources of biochemical oxygen demand to the San Joaquin River, California. Agric. Water Manage. 95, 527-538.

Stringfellow, W., Herr, J., Litton, G., Brunell, M., Borglin, S., Hanlon, J., Chen, C., Graham, J., Burks, R., Dahlgren, R., Kendall, C., Brown, R., Quinn, N., 2009. Investigation of river eutrophication as part of a low dissolved oxygen total maximum daily load implementation. Water Science and Technology 59, 9 - 14.

Stringfellow, W.T., Jain, R., 2010. Engineering the global ecosystem. Clean Technologies and Environmental Policy 12, 197-203.

Stringfellow, W.T., Karpuzcu, M.E., Spier, C., Hanlon, J.S., Graham, J., 2013. Sizing mitigation wetlands in agricultural watersheds. Water Science and Technology 67, 40-46.

Sullivan, A.B., Snyder, D.M., Rounds, S.A., 2010. Controls on biochemical oxygen demand in the upper Klamath River, Oregon. Chemical Geology 269, 12-21.

Systech Engineering Inc., 2012. WARMF Forecasting, Water Year 2012. Prepared for: Metropolitan Water District of Southern California, Walnut Creek, CA.

Systech Water Resources Inc., 2008. Final Report for the Task 6 Modeling of the San Joaquin River. Prepared for: CALFED Project ERP-02D-P63, Walnut Creek, CA.

U.S. Bureau of Reclamation, 2012a. Salt and Nitrate Budget Westside Salt Assessment, California Mid-Pacific Region, Attachment A: Water Quality Data Source Information. Department of the Interior, Washington, D.C.

U.S. Bureau of Reclamation, 2012b. Salt and Nitrate Budget: Westside Salt Assessment, California Mid-Pacific Region. Department of the Interior Washington, D.C.

Volkmar, E.C., Dahlgren, R.A., 2006. Biological oxygen demand dynamics in the lower San Joaquin River, California. Environmental Science and Technology 40, 5653-5660.

Volkmar, E.C., Henson, S.S., Dahlgren, R.A., O'Geen, A.T., Van Nieuwenhuyse, E.E., 2011. Diel patterns of algae and water quality constituents in the San Joaquin River, California, USA. Chemical Geology 283, 56-67.

Young, M., Kendall, C., 2007. DO TMDL Project March Annual Report 2007 Task 7: Biological Oxygen Demand (BOD) Isotope Study. U.S. Geological Survey, Menlo Park, CA.

Zamora, C., Dahlgren, R.A., Kratzer, C.R., Downing, B.D., Russell, A.D., Dileanis, P.D., Bergamaschi, B.A., Phillips, S.P., 2012. Groundwater contributions of flow, nitrate, and dissolved organic carbon to the lower San Joaquin River, California, during 2006-2008. Reston, VA.

Tables

Table 1. Technical reports from the DO Estuary Project which are supplemental material to this report. The technical reports can be downloaded from the Ecological Engineering Research Program website (http://www1.pacific.edu/eng/EERP2/).

Number	Report Name
4.1.1	Description and Photo-Documentation of Field Work Activities – Westside Monitoring Station Maintenance
4.1.2	Summary of Analytical Methods, Quality Assurance, and Quality Control for 2011 and 2012 Field Sampling and Laboratory Water Quality Analysis
4.2.1	Description and Photo-Documentation of Field Work Activities
4.2.2	Summary of 2011 and 2012 Field and Laboratory Water Quality Data
4.2.3	Temporal Plots of Field and Laboratory Data for Each Site Sampled in 2011 and 2012
4.3.1	Dissolved Oxygen Conditions in the Old and Middle Rivers in 2011 and 2012
4.4.1	Spatial Heterogeneity of Zooplankton in the Stockton Deep Water Ship Channel
4.4.2	Zooplankton Grazing Studies
4.5.1	Unprecedented Bloom of Toxin-Producing Cyanobacteria in the Southern Bay-Delta Estuary and its Potential Negative Impact on the Aquatic Food-Web
4.8.1	Using the WARMF 2008 Model to Quantitate the Effect of Nutrient Control and Tributary Inputs on Water Quality in the San Joaquin River
4.8.2	Analysis of the Gowdy Output Results from the SJR-WARMF 2012 Model
4.8.3	Mass Balance Analysis for the San Joaquin River from Lander Avenue to Vernalis
4.8.4	Methods for Direct Load Calculations in Agricultural Watersheds
4.8.5	Analysis of Link-Node Model Mass Loading Scenarios
4.8.6	High Resolution Dissolved Oxygen Profiling of the Stockton Deep Water Ship Channel during the Summer of 2012
4.8.7	High Resolution Salinity Profiling of the Stockton Deep Water Ship Channel during the Summer of 2012
4.8.8	SJR-WARMF 2008 and 2012 Error Analysis
5.1.1	Calibration of the Link-Node Model for Application to Understanding Causes of Low Dissolved Oxygen Conditions in the Stockton Deep Water Ship Channel
5.2.1	San Joaquin River Water Quality Modeling: Suspended Sediment Modeling of San Joaquin River in Watershed Analysis Risk Management Framework (WARMF) Model
5.2.2	Orestimba Creek Agricultural Drainage Study
5.2.3	Focused Agricultural Drainage Study: Calibration of the Orestimba Creek Watershed in the San Joaquin River WARMF Model
5.6.1	Inclusion of Zooplankton Population Dynamics in the Link-Node Model
6.1.1	Presentations and Abstracts for the Dissolved Oxygen– Total Maximum Daily Load Project
7.2.1	San Joaquin River Dissolved Oxygen Total Maximum Daily Load Program Long Term Monitoring Plan

Table 2. Total flows and loads of oxygen demanding substances (ODS) and ODS precursors as measured at Vernalis on the San Joaquin River. Annual loads and loads from the irrigation season (April through September) are presented for comparison.

Parameter	Total Load for 2007 (kg)	Load Agricultural Irrigation Season (kg)	Load Attributable to Irrigation Season (%)
Flow	16.9×10^{12}	7.9×10^{12}	46.7
BOD	5,489,323	3,638,423	66.3
Chl-a	49,976	38,448	76.9
Total Nitrogen	3,340,064	1,498,044	44.9
NO3-N	2,598,139	1,124,729	43.3
NH3-N	64,897	16,745	25.8
Organic Nitrogen	677,029	356,570	52.7
Total Phosphorus	318,406	136,109	42.7
Orthophosphate	183,324	78,887	43.0

Table 3. Locations on San Joaquin River (SJR) where flow and water quality were measured for a mass balance analysis. Each location is the last monitoring point on the respective tributary before discharge to the SJR.

Waterbody Name	Latitude	Longitude	Type	Predominant Flow Source
SJR[1] at Vernalis	37.67936	-121.26504	River	
SJR[1] at Maze Road	37.64027	-121.22952	River	
SJR[1] at Patterson	37.49415	-121.08071	River	
SJR[1] at Crows Landing	37.43197	-121.01165	River	
SJR[1] at Lander Avenue	37.29502	-120.85105	River	Agricultural and Sierra drainage
Stanislaus River	37.70160	-121.17719	Tributary	Sierra drainage
Tuolumne River	37.60288	-121.13141	Tributary	Sierra drainage
Merced River	37.35043	-120.96196	Tributary	Sierra drainage
Mud Slough	37.26250	-120.90555	Tributary	Agricultural and wetland drainage
Salt Slough	37.24768	-120.85186	Tributary	Agricultural and wetland drainage
Los Banos Creek	37.27546	-120.95532	Tributary	Agricultural and wetland drainage
Orestimba Creek	37.41396	-121.01488	Tributary	Agricultural drainage
MID[2] Lateral 4	37.63057	-121.15888	Drain/Spill	Agricultural drainage
MID[2] Miller Lake	37.54242	-121.09426	Drain/Spill	Agricultural and wetland drainage
TID[3] Lateral 2	37.56522	-121.13836	Drain/Spill	Agricultural drainage
TID[3] Westport Drain	37.54242	-121.09426	Drain/Spill	Agricultural drainage
TID[3] Harding Drain	37.46427	-121.03093	Drain/Spill	Agricultural and urban drainage
TID[3] Lateral 6 & 7	37.39767	-120.95957	Drain/Spill	Agricultural drainage
Hospital Creek	37.60026	-121.22506	Drain	Agricultural drainage
Ingram Creek	37.60026	-121.22506	Drain	Agricultural drainage
Westley Wasteway	37.55818	-121.16375	Drain	Agricultural drainage
Del Puerto Creek	37.53947	-121.12206	Drain	Agricultural drainage
Marshall Road Drain	37.43605	-121.03600	Drain	Agricultural drainage
Patterson Irrigation District Diversion	37.49716	-121.08280	Diversion	San Joaquin River
West Stanislaus Irrigation District Diversion	37.58438	-121.20100	Diversion	San Joaquin River
El Solyo Pumping Station	37.64010	-121.22950	Diversion	San Joaquin River
Ramona Lake Drain	37.47881	-121.06850	Drain	Agricultural drainage
Moran Drain	37.43547	-121.03551	Drain	Agricultural drainage
Spanish Grant Drain	37.43576	-121.03581	Drain	Agricultural drainage

[1]SJR: San Joaquin River, [2]MID: Modesto Irrigation District, [3]TID: Turlock Irrigation District

Table 4. Summary statistics for all model output using the May_2013 version of the Link-Node model and observed data. The baseline scenario includes all factors contributing to excess net oxygen demand (ENOD). The baseline is compared to scenarios where major factors contributing to ENOD are excluded, including reducing the depth of the DWSC from 40 feet to 12.5 feet deep (No DWSC), removing the oxygen demanding substances (ODS) from the Stockton regional wastewater control facility (No RWCF), removing the ODS from the San Joaquin River (No SJR), and removing the ODS from local, predominately urban, tributaries discharging into the DWSC (No Trib).

Summary Statistic	RRI[1] Observed	Baseline scenario	No DWSC scenario	No RWCF scenario	No SJR scenario	No Trib scenario	Flow+500 scenario
Mean DO (mg L^{-1})	7.74	7.53	8.03	7.63	8.19	7.61	7.63
Min DO (mg L^{-1})	1.80	4.83	4.94	4.91	4.90	4.93	5.10
Max DO (mg L^{-1})	13.7	10.2	10.9	10.4	11.1	10.3	10.3
Std. Dev. DO (mg L^{-1})	1.64	1.13	1.15	1.12	1.24	1.13	1.08
N	52,511	52,511	52,511	52,511	52,511	52,511	52,511

[1]Observed dissolved oxygen at Rough & Ready Island for the time period January 1, 2005 to December 31, 2011.

Table 5. Summary statistics for model output when DO concentrations were below objectives, using the May_2013 version of the Link-Node model. The baseline scenario includes all factors contributing to excess net oxygen demand (ENOD). The baseline is compared to scenarios where major factors contributing to ENOD are excluded, including reducing the depth of the DWSC from 40 to 12.5 feet deep (No DWSC), removing the oxygen demanding substances (ODS) from the Stockton wastewater treatment facility (No RWCF), removing the ODS from the San Joaquin River (No SJR), and removing the ODS from local, predominately urban tributaries discharging into the DWSC (No Trib).

Summary Statistic	Baseline scenario	No DWSC scenario	No RWCF scenario	No SJR scenario	No Trib scenario	Flow+500 scenario
Mean DO (mg L^{-1})	5.43	6.08	5.68	5.85	5.53	5.82
Min DO (mg L^{-1})	4.83	5.16	4.91	4.90	4.93	5.10
Max DO (mg L^{-1})	6.00	7.16	6.59	7.18	6.12	6.48
Std. Dev. DO (mg L^{-1})	0.34	0.53	0.49	0.54	0.329	0.35
N	2,007	2,007	2,007	2,007	2,007	2,007

Table 6. Summary statistics of the difference between the excess net oxygen demand (ENOD) from January 1, 2005 through December 31, 2010 for the model baseline and each Link-Node model scenario generated using the May_2013 model. These values represent the predicted improvement (reduced ENOD) for the scenarios relative to the baseline. Excess net oxygen demand (ENOD) was not calculated for net flows equal to or less than zero. The baseline scenario includes all factors contributing to excess net oxygen demand (ENOD). The baseline is compared to scenarios where major factors contributing to ENOD are excluded, including reducing the depth of the DWSC from 30 to 12 feet deep (No DWSC), removing the oxygen demanding substances (ODS) from the Stockton wastewater treatment facility (No RWCF) the ODS from the San Joaquin River (No SJR), and ODS from local, predominately urban tributaries discharging into the DWSC (No Trib) and increasing flows by 500 cfs with no change in water quality (Flow+500).

Summary Statistic	No DWSC scenario	No RWCF scenario	No SJR scenario	No Trib scenario	Flow+500 scenario
Mean ENOD Improvement (kg d^{-1})	1,154	366	929	150	513
Min ENOD Improvement (kg d^{-1})	28.4	6.26	9.12	7.48	-850
Max ENOD Improvement (kg d^{-1})	6,105	4,225	5,971	637	1,634
Std. Dev. ENOD Improvement (kg d^{-1})	1,029	720	1,268	89.8	527
N	1,171	1,171	1,171	1,171	1,769

Figures

Figure 1. The San Joaquin River watershed.

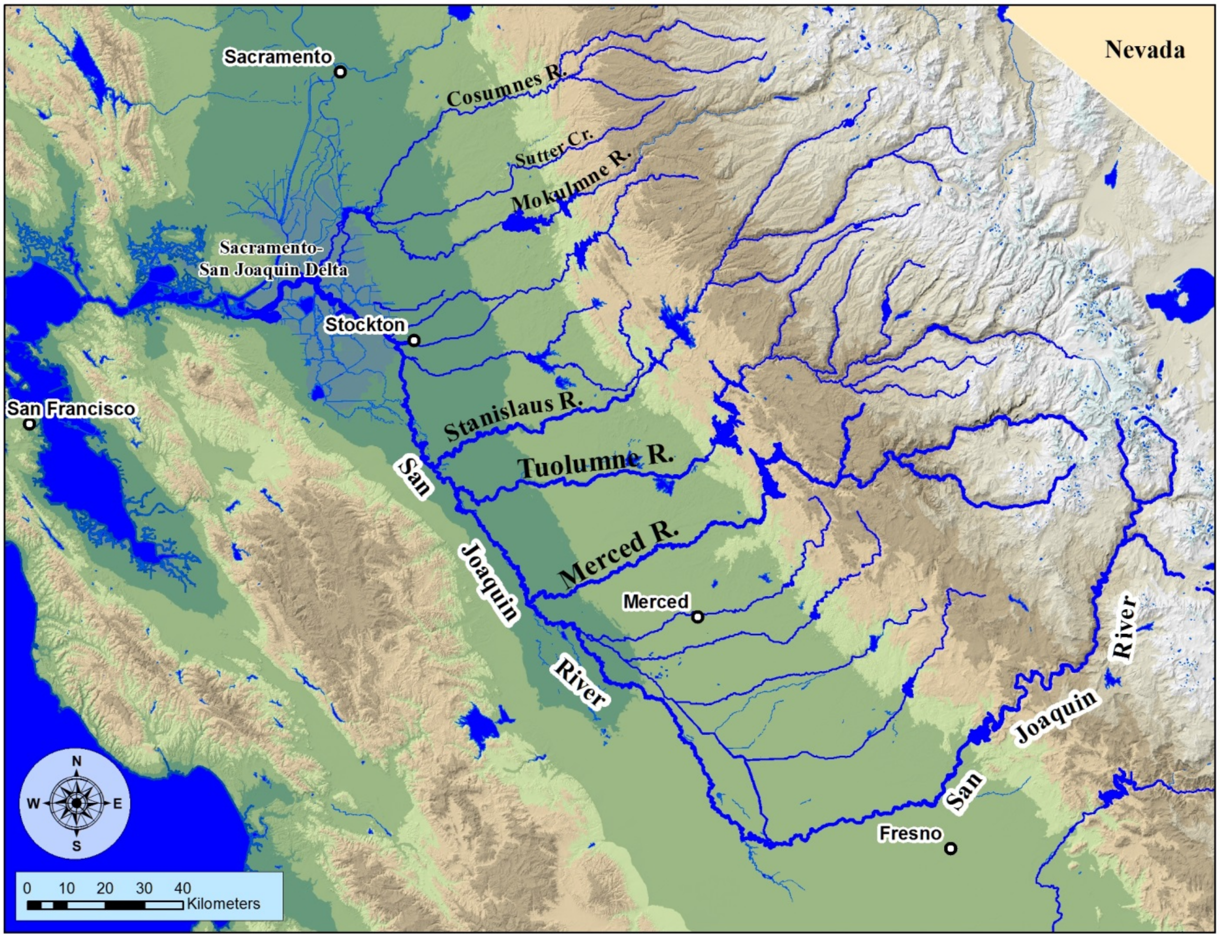
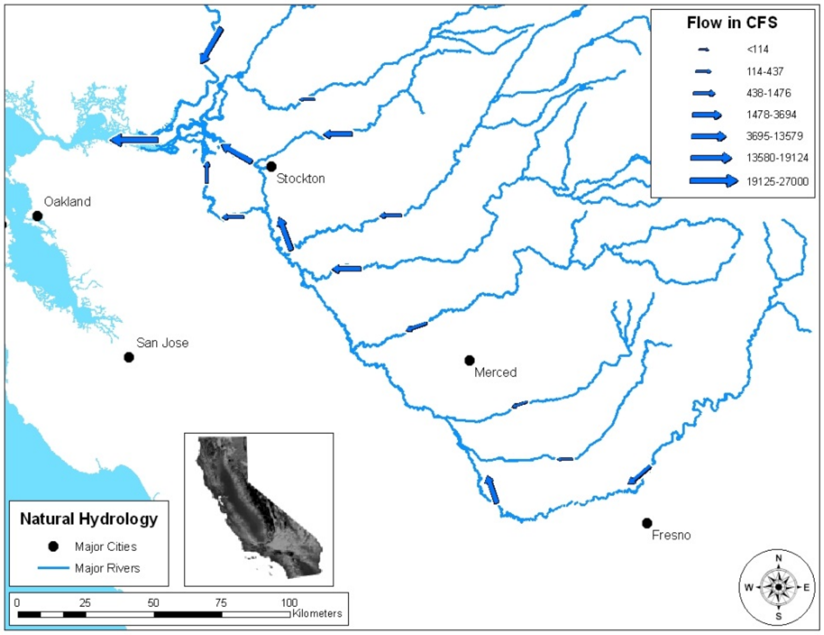


Figure 2: The hydrology of the San Joaquin River Valley has been modified to provide social and economic benefit to California. Loss of ecosystem services was not considered in the original engineering design.

a. Natural hydrology of the San Joaquin River Valley, CA (simplified).



b. Current hydrology of the San Joaquin River Valley, CA (simplified).

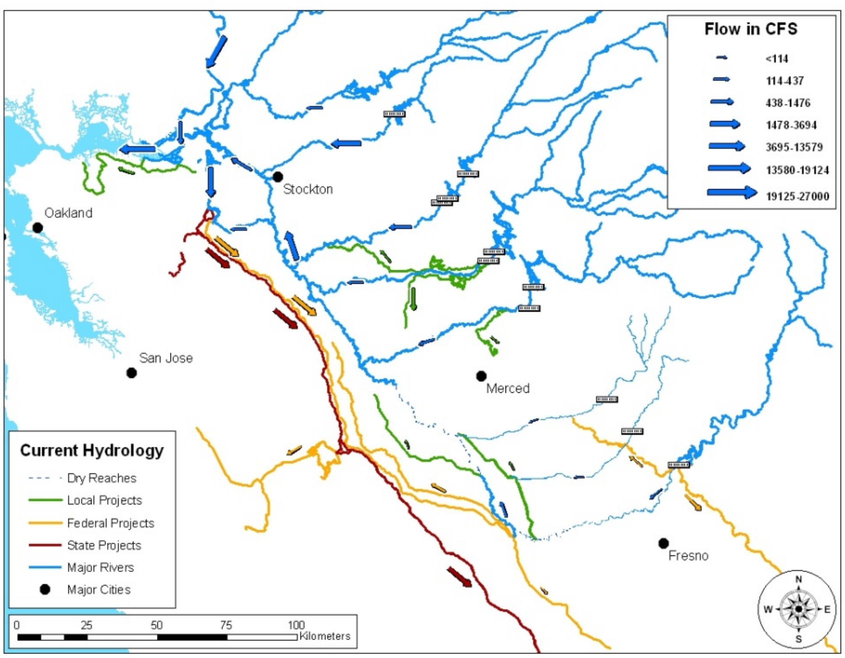


Figure 3: The San Joaquin River Estuary, showing in red the waterbodies on the 2010 California 303(d) list as impaired for low dissolved oxygen.

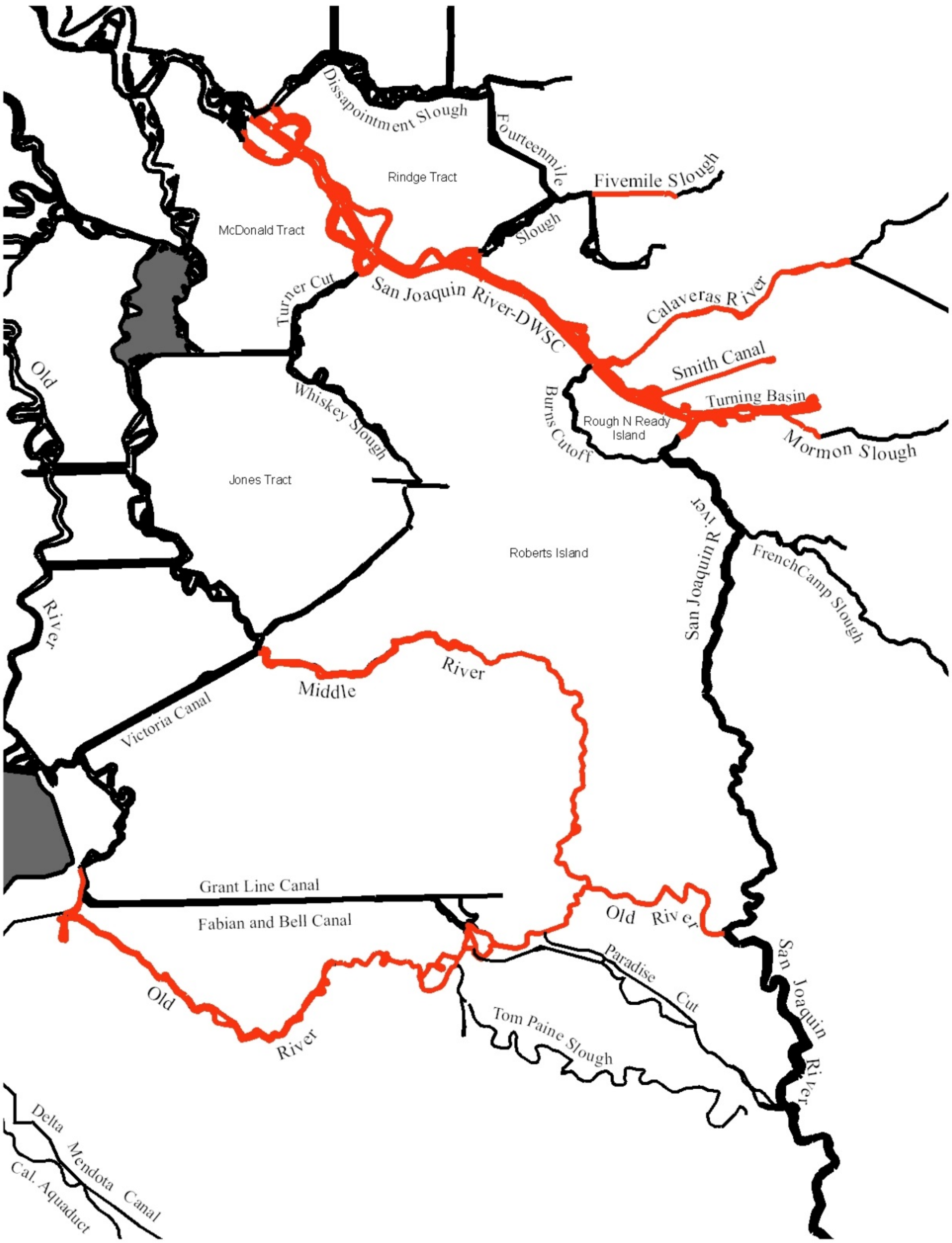


Figure 4. San Joaquin River dissolved oxygen (DO) total maximum daily load (TMDL) source area as defined by Control Plan (California Regional Water Quality Control Board Central Valley Region, 2005).

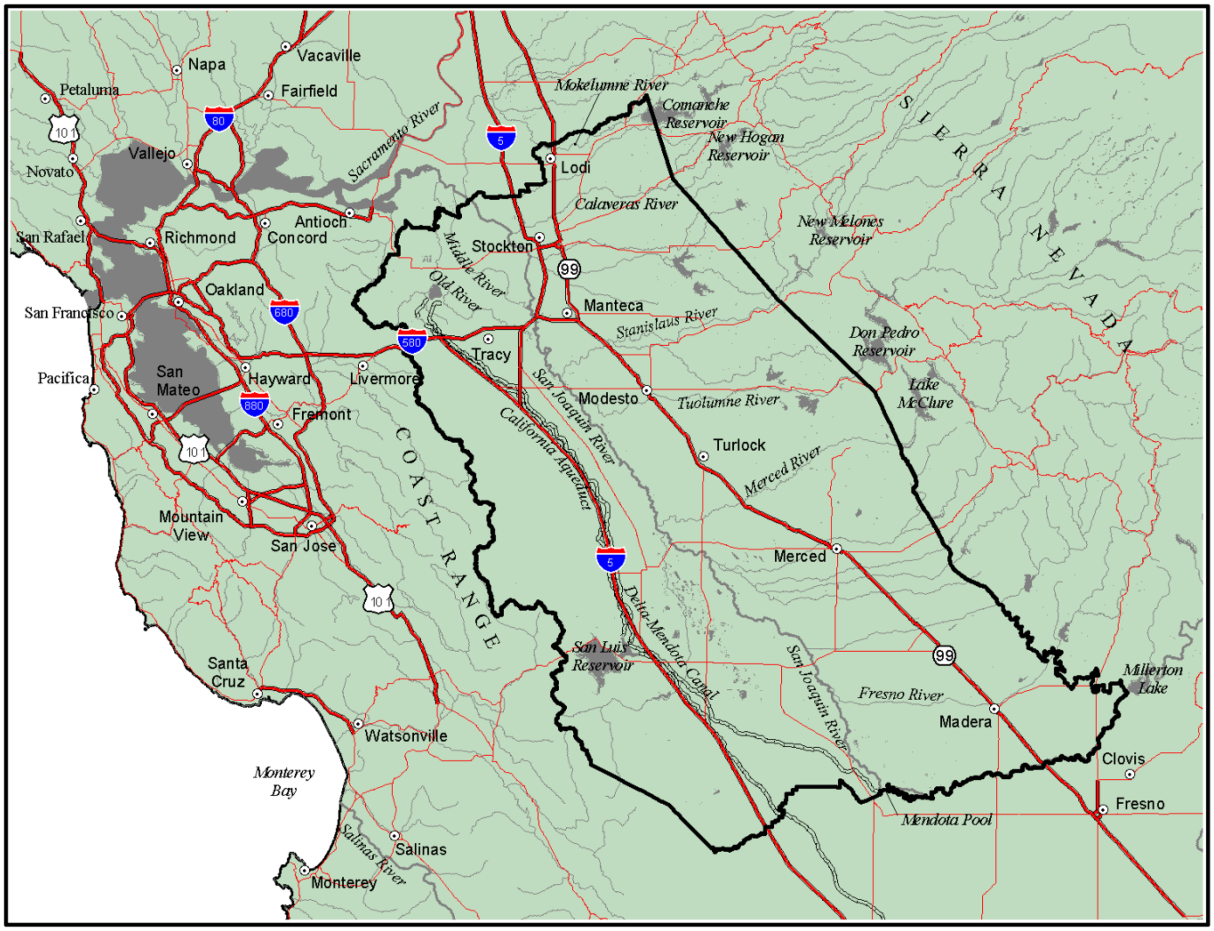


Figure 5. Study area and sampling locations for the Upstream and Estuary Projects. For the Upstream project, investigations were largely limited to the riverine portion of the San Joaquin River, upstream (south) of the Vernalis monitoring location (5) and downstream (north) of where the Lander Ave bridge crosses the San Joaquin River (10). The Estuary Project focused on the tidal estuary downstream (north) of Vernalis, which is the legal limit of the Sacramento-San Joaquin Delta Estuary.

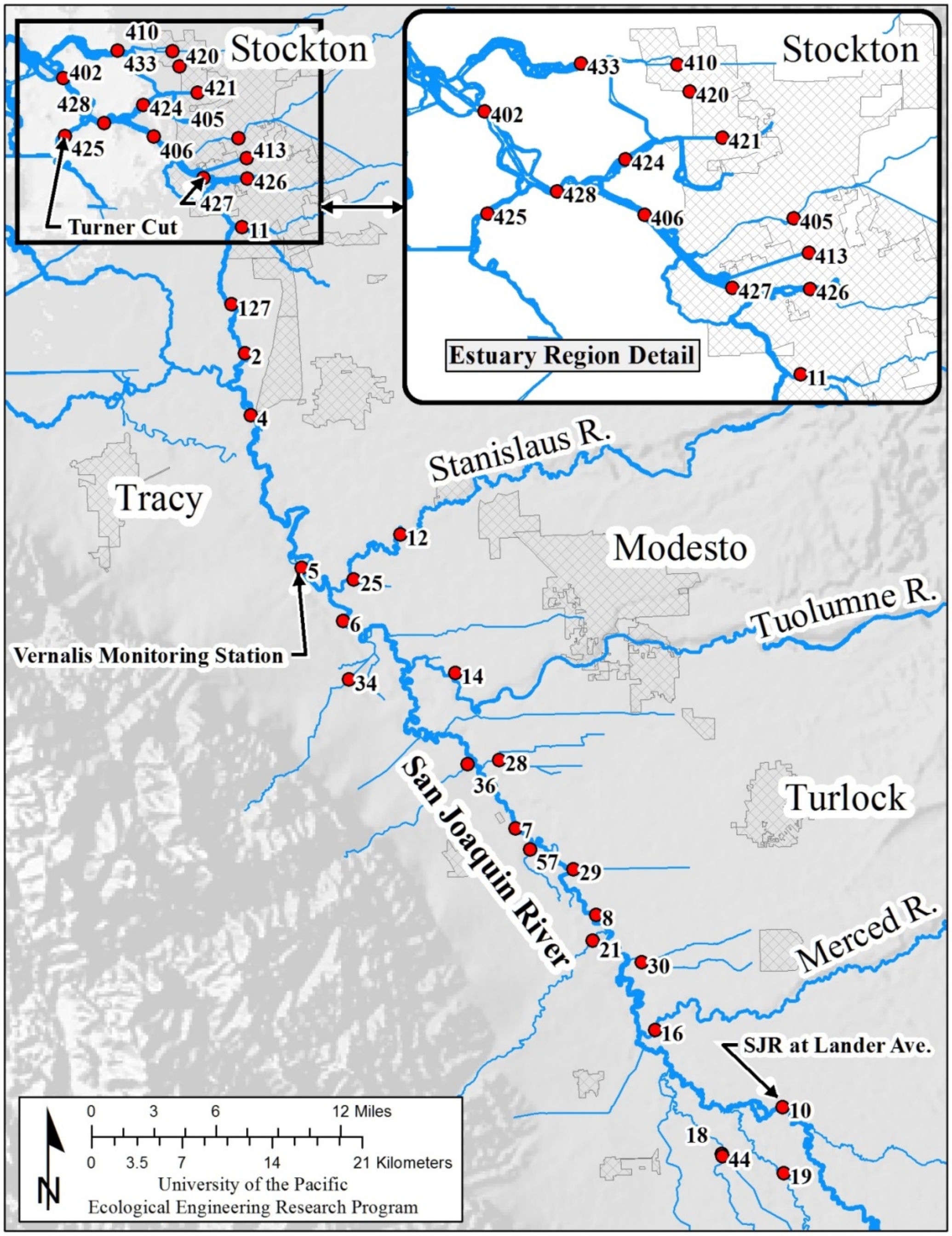


Figure 6. Link-Node model domain from Chen and Tsai (2002b). The San Joaquin River at Rough & Ready Island is denoted by Node 40. The Stockton RWCF discharge into the San Joaquin River occurs between Node 25 and Node 26 in the model.

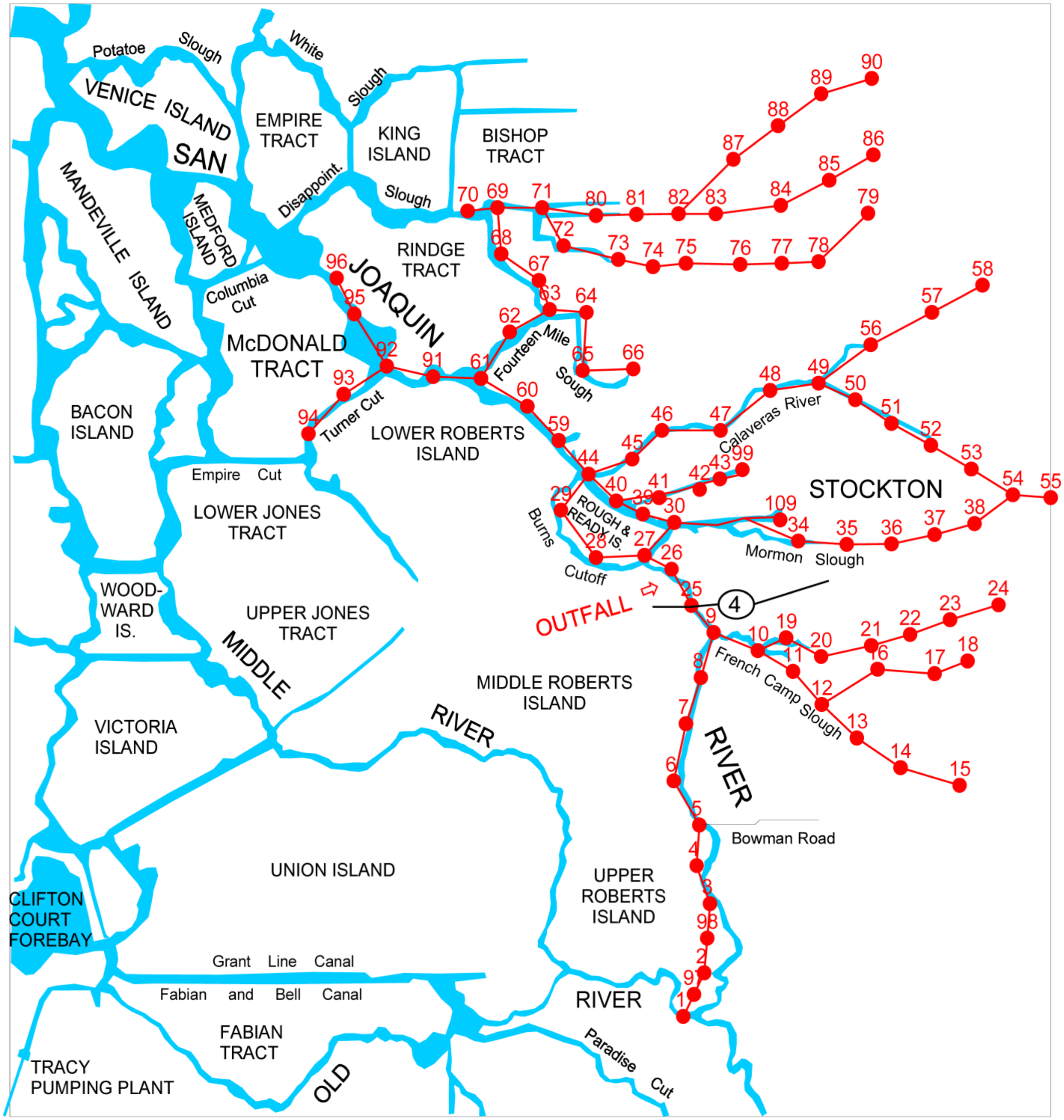


Figure 7. Landuse in San Joaquin, Stanislaus, and Merced Counties is predominated by agriculture. Urban land areas are characterized by low density populations and most domestic and industrial wastewater discharge is land applied or treated by septic systems.

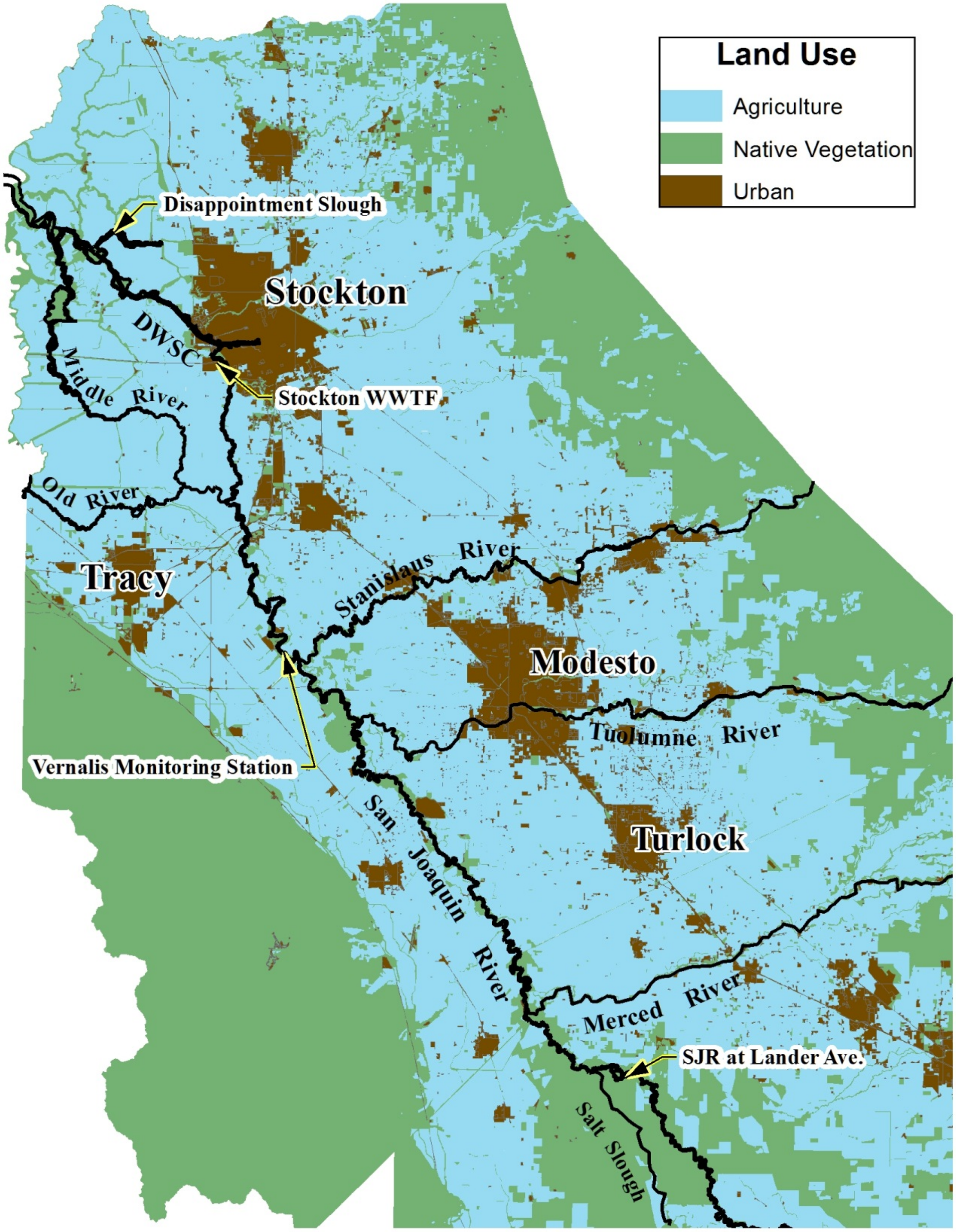


Figure 8. Schematic chart of flows entering the San Joaquin River between Lander Ave. and Vernalis.

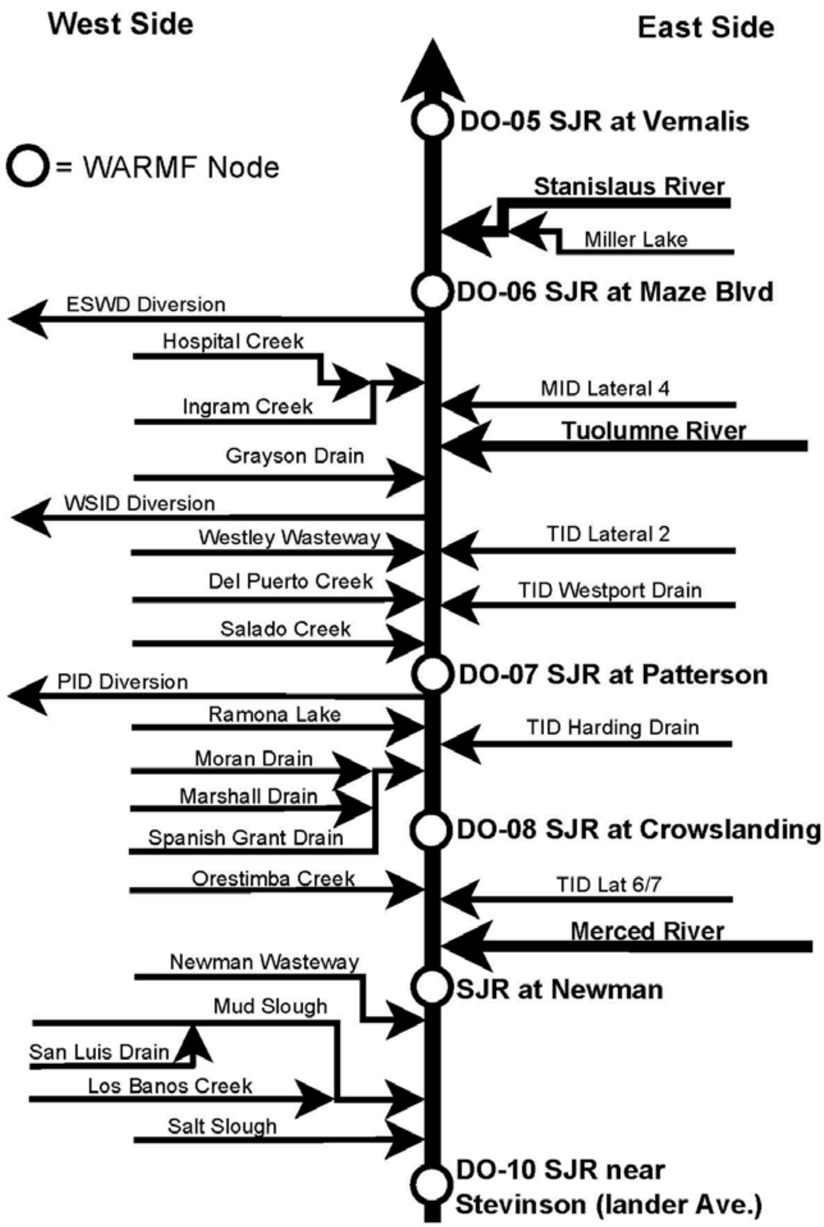


Figure 9. Expected dissolved oxygen (DO) improvement resulting from scenarios in the May 2013 Link-Node model.

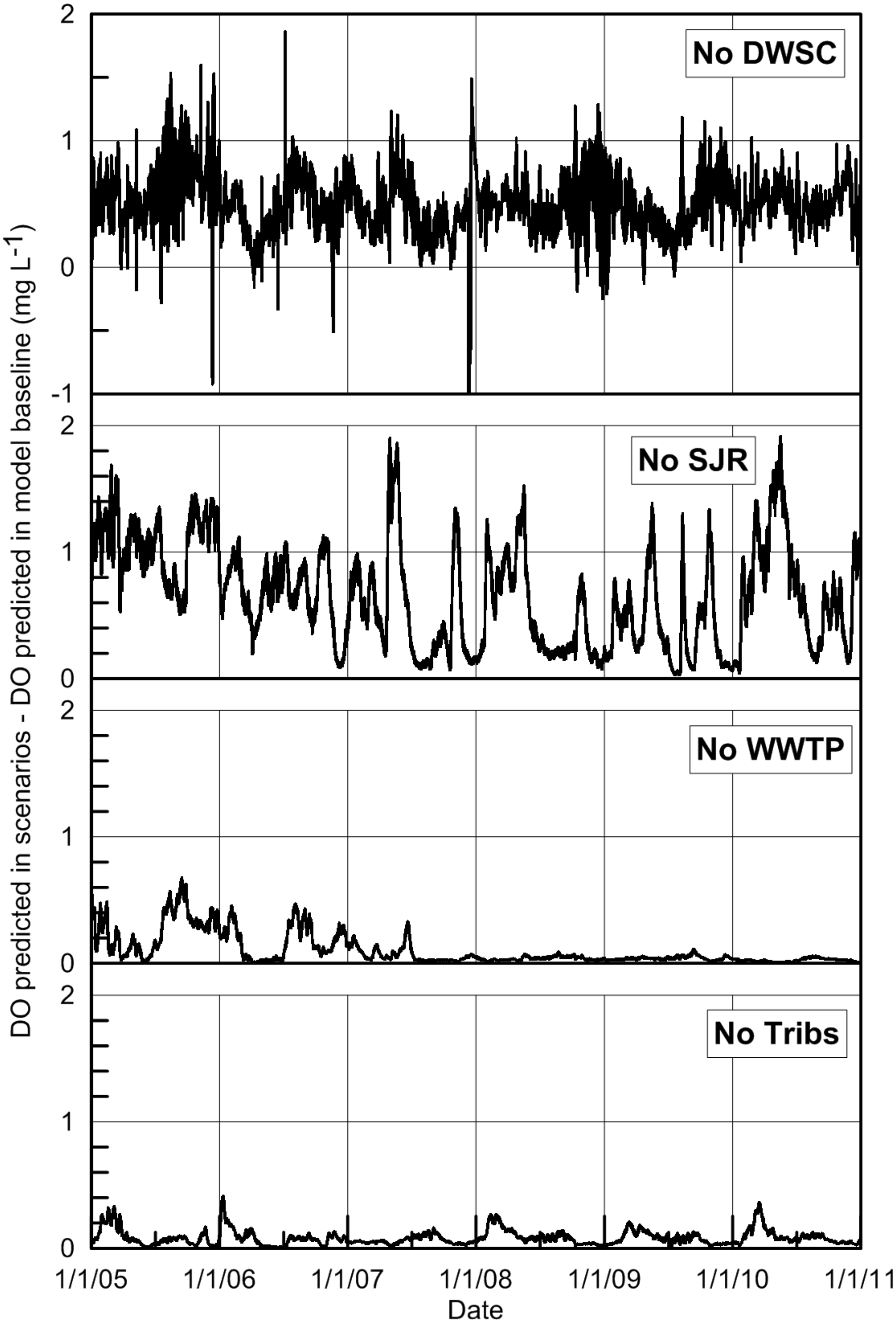


Figure 10. Excess net oxygen demand (ENOD) for the May 2013 Link-Node model scenarios compared to the baseline scenario. Positive values represent the load of oxygen needed to meet the standard, while negative values represent the load of oxygen demand that can be assimilated without violating the DO standard. The dashed lines delineate the start and end of a year. Smaller (more negative) values are considered more responsible for violations than larger (more positive) values.

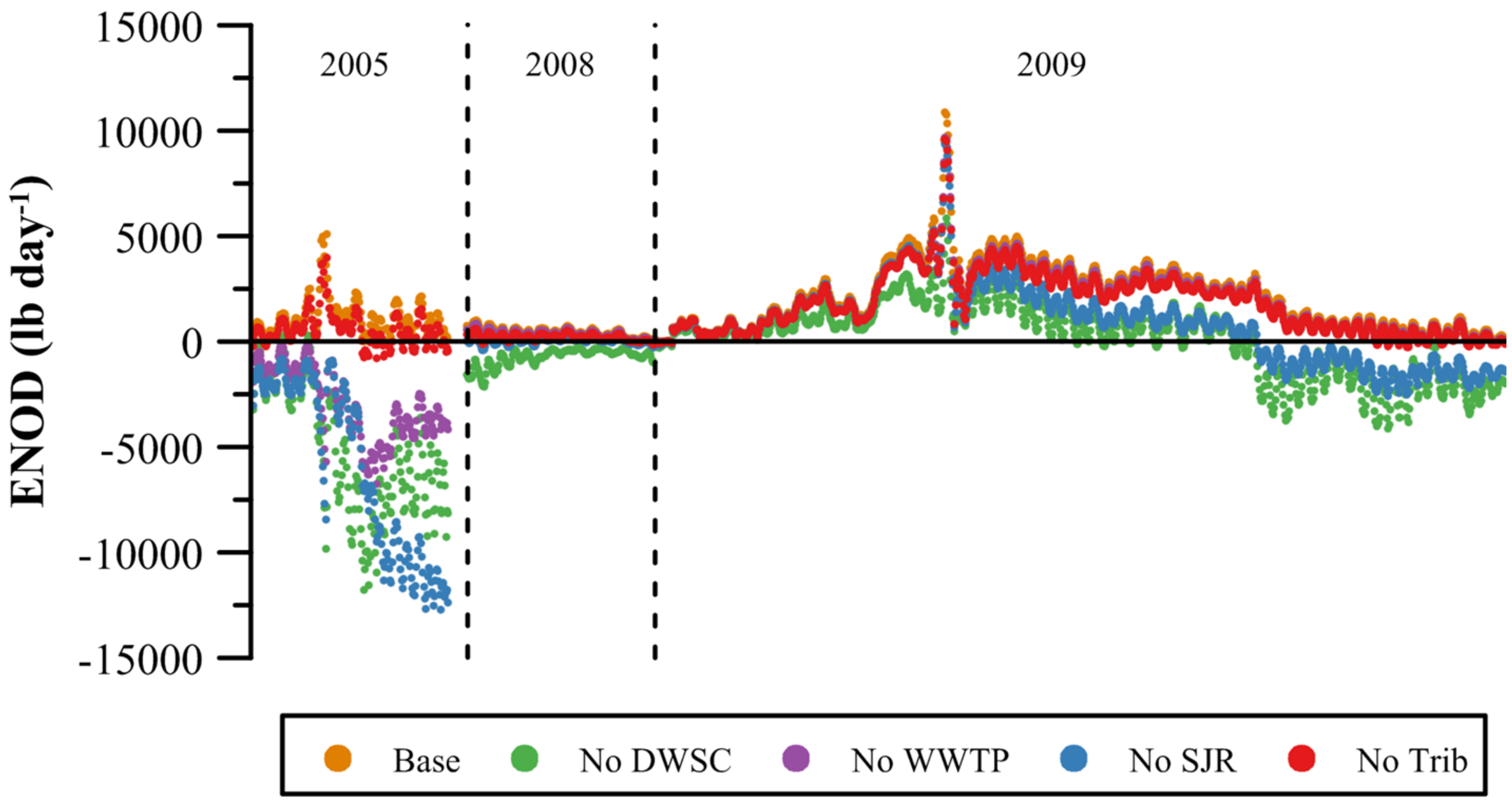


Figure 11. Mass load of total ammonia nitrogen (nitrogen from ammonium and aqueous ammonia) from the Stockton Regional Wastewater Control Facility (RWCF). The facility was renovated in 2007 to include constructed wetlands and a nitrification facility.

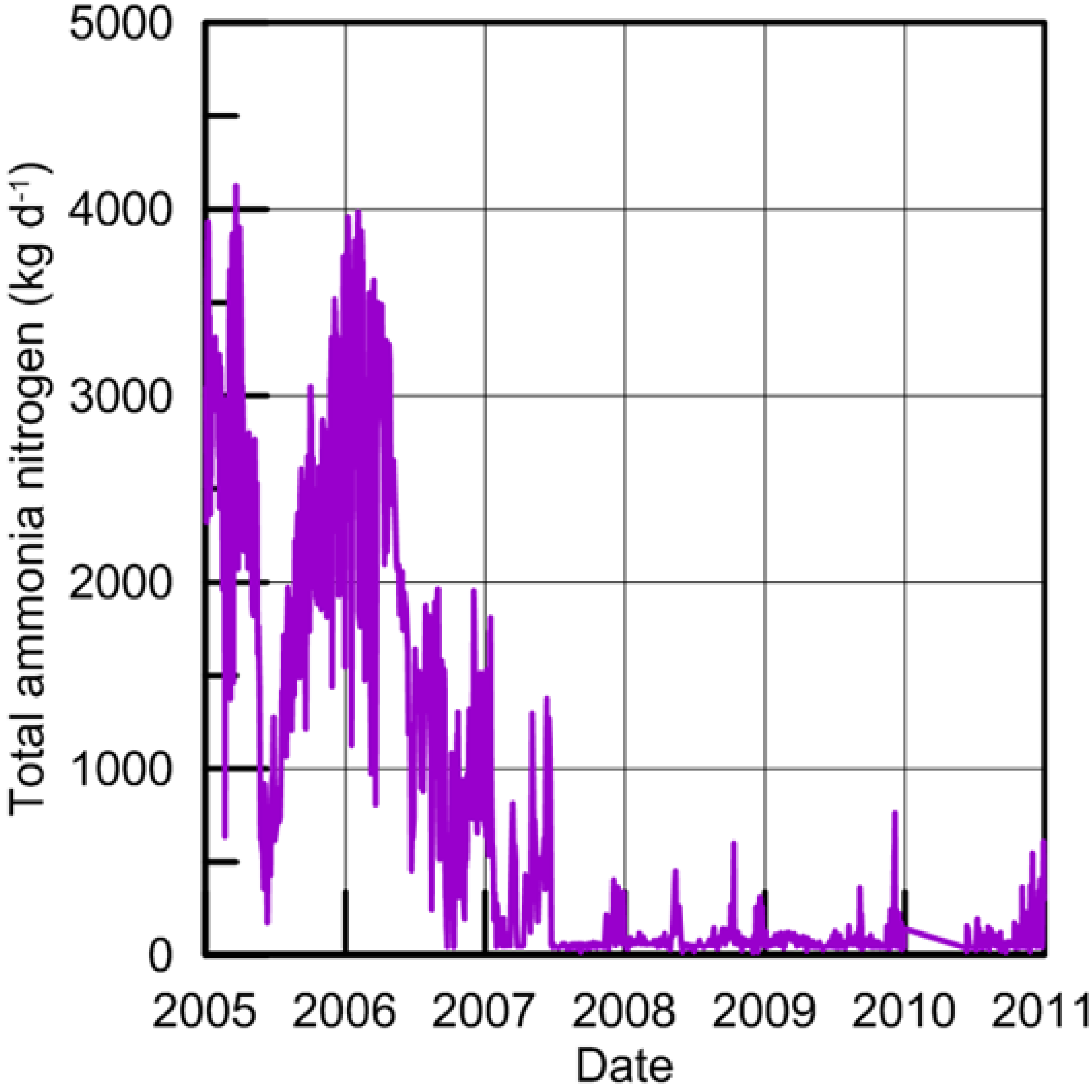


Figure 12. Mass load of carbonaceous biochemical oxygen demand (cBOD) from the Stockton Regional Wastewater Control Facility (RWCF). The facility was renovated in 2007 to include constructed wetlands and a nitrification facility.

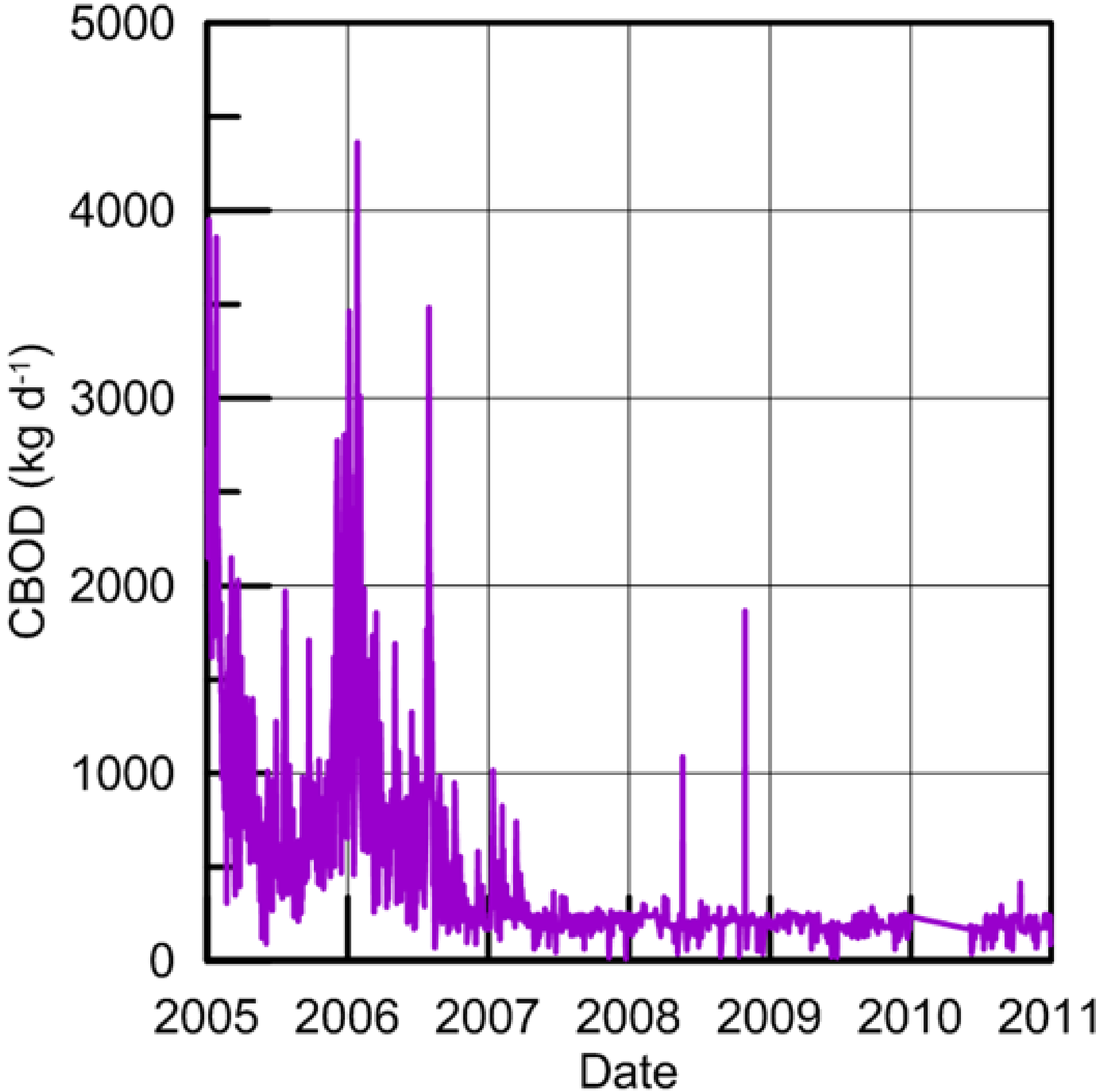


Figure 13. Dissolved oxygen (DO) improvement as predicted by the model, between the baseline and Flow+500 cfs scenarios for the May_2013 Link-Node model calibration.

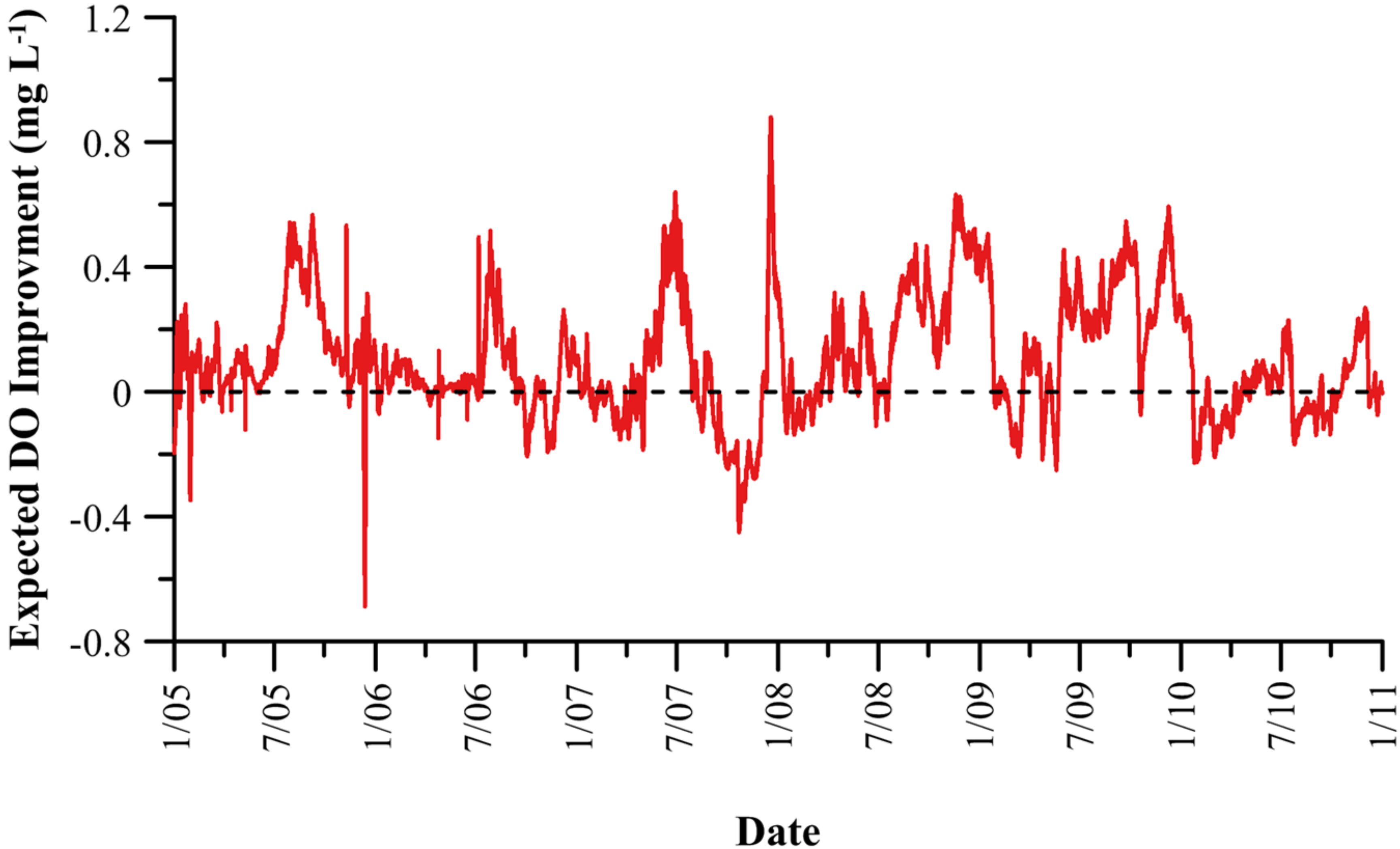


Figure 14. Excess Net Oxygen Demand (ENOD), as predicted by the model, for the baseline and Flow+500 cfs scenarios in May_2013 Link-Node model calibration.

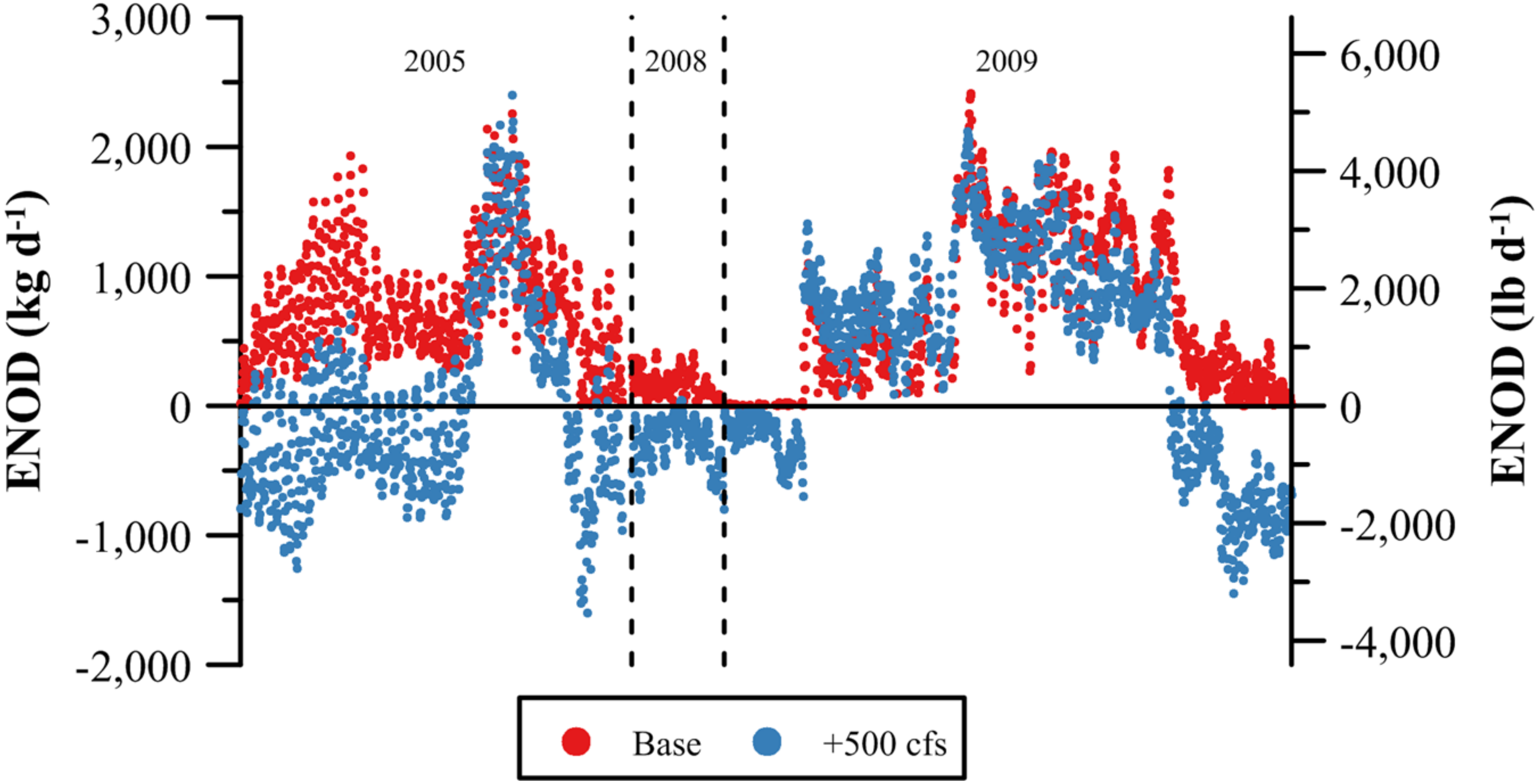


Figure 15. Daily minimum dissolved oxygen (DO) concentration versus daily net flow January 2005 to August 2011. Only one DO violation occurred (on August 17, 2005) when flows were above 3000 cfs in the 2005-2011 time period.